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First Quarterly Report

For

PASSIVE SOLAR ARRAY ORIENTATION SYSTEM (THERMAL HELIOTROPE)

(23 December 1969 – 23 March 1969)

Contract No. NAS 5-11637

Prepared by

Electrical Power Systems
Space Systems Division
Lockheed Missiles & Space Company
A Group Division of Lockheed Aircarft Corporation
Sunnyvale, California 94088

For

Goddard Space Flight Center
Greenbelt, Maryland 20771

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Contract No.: NAS 5-11637
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SUMMARY

A. OBJECTIVE

Solar array tracking systems to date have been complex electromechanical assemblies. The objective of this program is to evaluate the feasibility of simple passive tracking concepts using bimetal elements. This evaluation includes an examination of the requirements for such devices, the development of thermal heliotrope concepts for selected requirements, analysis and design implementation of these concepts, and fabrication and testing of models of the preferred designs.

B. SCOPE OF WORK

The scope of the work for the period reported herein has been to survey general array tracking requirements for common orbits and altitudes and to devise thermal heliotrope concepts applicable to the common orbits. In support of these investigations a review of bimetal theory, construction, and operation has been conducted. In addition, a thermal analysis was conducted to categorize general temperature constraints.

C. CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations are made and discussed in the text of this report:

- Three mission categories are recommended for tracking system designs: 200-nm low earth orbital, 8100-nm 28.5-degree inclination intermediate orbit, and synchronous equatorial orbit.
- Existing slow tracking rates were found to be well within the limits of thermal heliotrope acceleration torque capability.
- Trackers should, as a design goal, be capable of recovery from a high degree of solar array misorientation.

- Most earth orbital tracking will be unidirectional, whether the vehicle is launched from ETR or WTR, thereby enhancing greatly the adaptability of thermal tracking devices.
- Bimetal coil response can be optimized by appropriate thermal coatings. Most applications require high absorbtance and low emittance coatings.
- Detent/snap tracker concepts require locks or brakes to prevent inertia overrun.
- Four concepts have been developed to date:

  a. Locking ratchet detent device – features incremental tracking with positive mechanical stop to prevent inertial overrun

  b. Brake detent device – a continuous tracker with automatic braking action to prevent override

  c. Stored energy tracker – a 2-coil device allowing separate optimization of energy storage and sensing functions

  d. Seasonal adjust device – provides bidirectional seasonal adjust capability.

- A study of torque multiplication techniques has resulted in two methods for increasing tracking torque if necessary.

Progress to date has indicated definite promise for application of thermal heliotrope concepts for sun tracking. Detailed tracker designs will depend on specific vehicle applications, but the concepts can be proven by model testing.

During the next quarter more concepts will be evaluated and final selection will be made of four tracking devices. These models will be designed and fabricated, and thermal-vacuum testing will be initiated.

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SECTION I
INTRODUCTION

A. ABSTRACT

The object of this document is to report the progress of the first three-month period of a nine-month study to evaluate the feasibility of thermally actuated sun-tracking systems. These systems use bimetal elements for both sensing and motive power.

The project concerns itself with exploring the feasibility of providing solar array sun-tracking capability through the use of non-electrical devices. It consists of five main tasks.

- Survey general tracking requirements such as rate and torque requirements
- Study thermal heliotrope operating mechanisms and develop concepts
- Analyze thermal properties and provide conceptual designs
- Fabricate and test models in simulated orbit environments
- Document findings and recommendations

The general constraints associated with thermal tracking systems have been examined and typical earth orbiting missions categorized. The possibility of two-axis tracking has also been considered. A detailed presentation of the theory of bimetal elements is given with specific formulas for helical bimetal coils. Preliminary thermal analyses have indicated factors influencing response times of the coils and appropriate thermal coatings for them. Several concepts for thermal heliotrope trackers have been developed. To date two of these have been chosen for model tests in a thermal-vacuum orbit environment. Fabrication of the first models is underway.

B. NOMENCLATURE

Symbol

A	angle of rotation
E	modulus of elasticity
ETR	Eastern Test Range
F	flexivity
I	mass moment of inertia
L	active length
M	mass
NP	noon point
R	radius of curvature
S	solar flux constant
T	temperature
WTR	Western Test Range
a	bimetal component thickness
b	array width
c	heat capacity
m	a_2/a_1
n	E_2/E_1
r	radius of gyration
t	thickness
w	width
δ	coefficient of thermal expansion
λ	angular acceleration
α	solar absorbtance
α	orbit plane – array axis angle
β	orbit plane – earth sun angle
ϵ	emissivity
ϕ	tracking increment angle
$\theta/2$	array misorientation angle
τ	time
Γ	torque
ω	angular velocity

Subscript

c	coil
e	equilibrium
f	final
i	initial, input
o	output
p	projected
s	sink
t	total

SECTION II
TECHNICAL DISCUSSION

A. GENERAL TRACKING CONSTRAINTS

Certain general constraints govern the application of sun-tracking systems to orbiting vehicles. Among these are considerations of array size, required tracking rates, interaction with vehicle control systems, device bearing techniques, and interface harnessing.

1. Array Sizes and Inertias

Solar array sizes vary widely from program to program depending upon power requirements, orbit paths, and array configurations. The mass moment of inertia of a relatively thin flat plate is approximated by:

$$I = \frac{1}{12} Mb^2 = \frac{4}{3} Mr^2$$

It is evident that inertias depend greatly on array width, b , as well as total mass. Some examples of array sizes representative of previous hardware items are given below:

Array Type	LMSC Type II	LMSC Type III	Nimbus	LMSC Flex
Width (ft)	4.8	3.0	8.0	5.3
Length (ft)	19.2	6.7	3.1	11.5
Wing Area (ft^2)	92	20	25	50
Radius of Gyration (ft)	1.17	0.75	2.00	1.31
Moment of inertia (slug-ft^2)	7.75	0.70	6.02	1.24
Array and Support Density (lb/ft^2)	1.47	1.50	1.45	0.25

The shape of a solar array is largely determined by the space allocation on the vehicle and by the array placement and shading considerations. Many different designs have evolved associated with body-mounted panels; however, this study is only concerned with arrays or panels that project from the vehicle in a swing-out or deployable fashion and that can be oriented for sun tracking.

Because of array shading that can occur with an array nested closely alongside the vehicle (Figure 1) and in order to obtain rotational freedom, it is desirable to provide sufficient vehicle/array displacement to minimize shading and mechanical interference. Where higher power requirements dictate large array areas, it is often most feasible to add the area on the outboard end of the array, away from possible shading and rotational interference. Therefore, the array would tend to assume a rectangular shape with its smaller dimension adjacent to the vehicle.

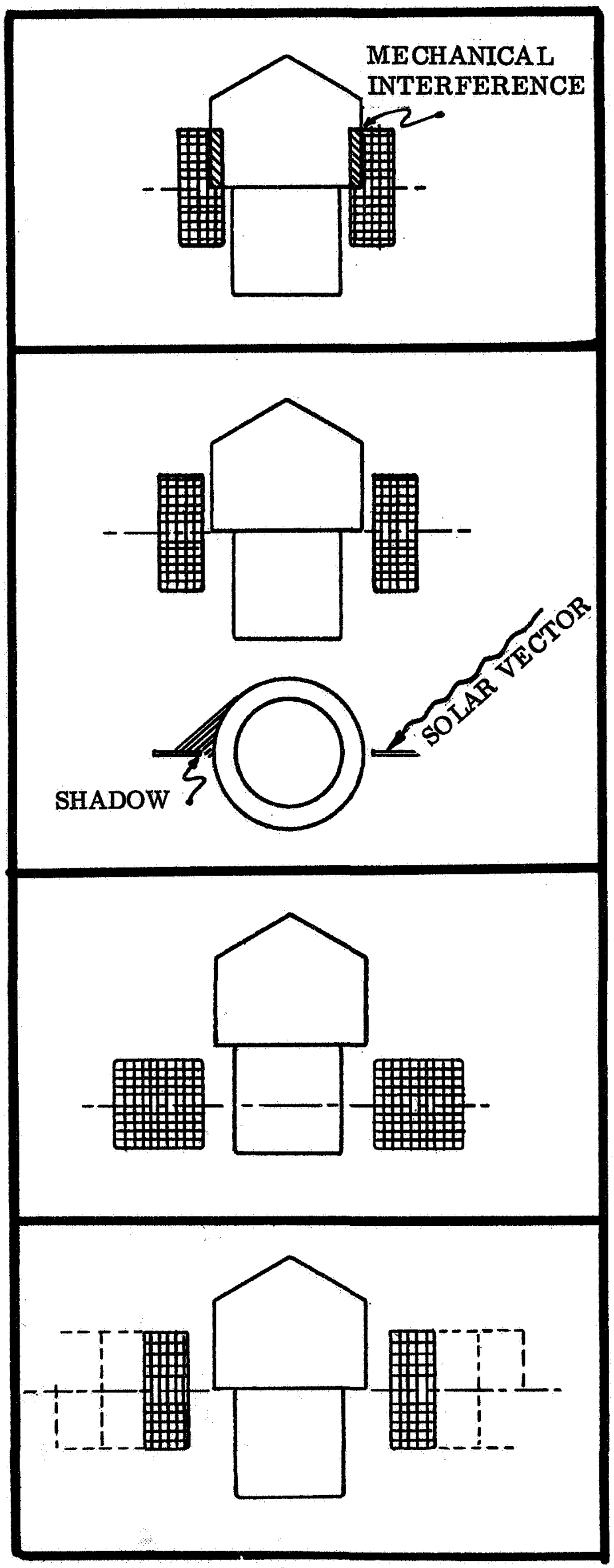
A basic assumption is made that the primary application of the thermal heliotrope is on three-axis stabilized vehicles with earth or orbited body orientation. Obviously, a sun-oriented vehicle would not require the tracking device. Spin-stabilized vehicles are normally of a symmetrical configuration, usually a cylinder, with the outside periphery covered with body-mounted cells. Their rotational rate is much in excess of the response rate of the bimetal devices being currently examined; therefore, spin-stabilized vehicles with despun arrays or antennas will not be considered.

2. Array Tracking Parameters and Acceleration

As can be seen in Figure 2 for earth-orbiting vehicles, the fastest tracking rate to be considered is in the order of 4 deg per minute. This would be 0.011 rpm, a relatively slow rotational rate. At synchronous altitudes the orbital rate is 0.25 deg per minute with respect to the earth-sun line. This is only 0.000688 rpm.

With this range of orbital rate it is apparent that acceleration can be very minute to arrive at tracking velocity and still maintain adequate response and tracking accuracy. The thermal heliotrope devices are inherently slow response devices with extremely low inertia change, unlike gear head reduction motors. Drive devices such as

FIGURE 1
ARRAY PLACEMENT – SIZE CONSIDERATIONS



The arrays must have a shape or displacement from the vehicle such that rotational interference does not occur.

Proximity to the vehicle is selected by consideration of the maximum solar incidence angles and resulting array shading.

The positioning and sizes of the arrays may be dictated in main by available space allocation on the vehicle.

Growth most often occurs on the outboard end of the arrays such that the rotational axis becomes the major axis of the array.

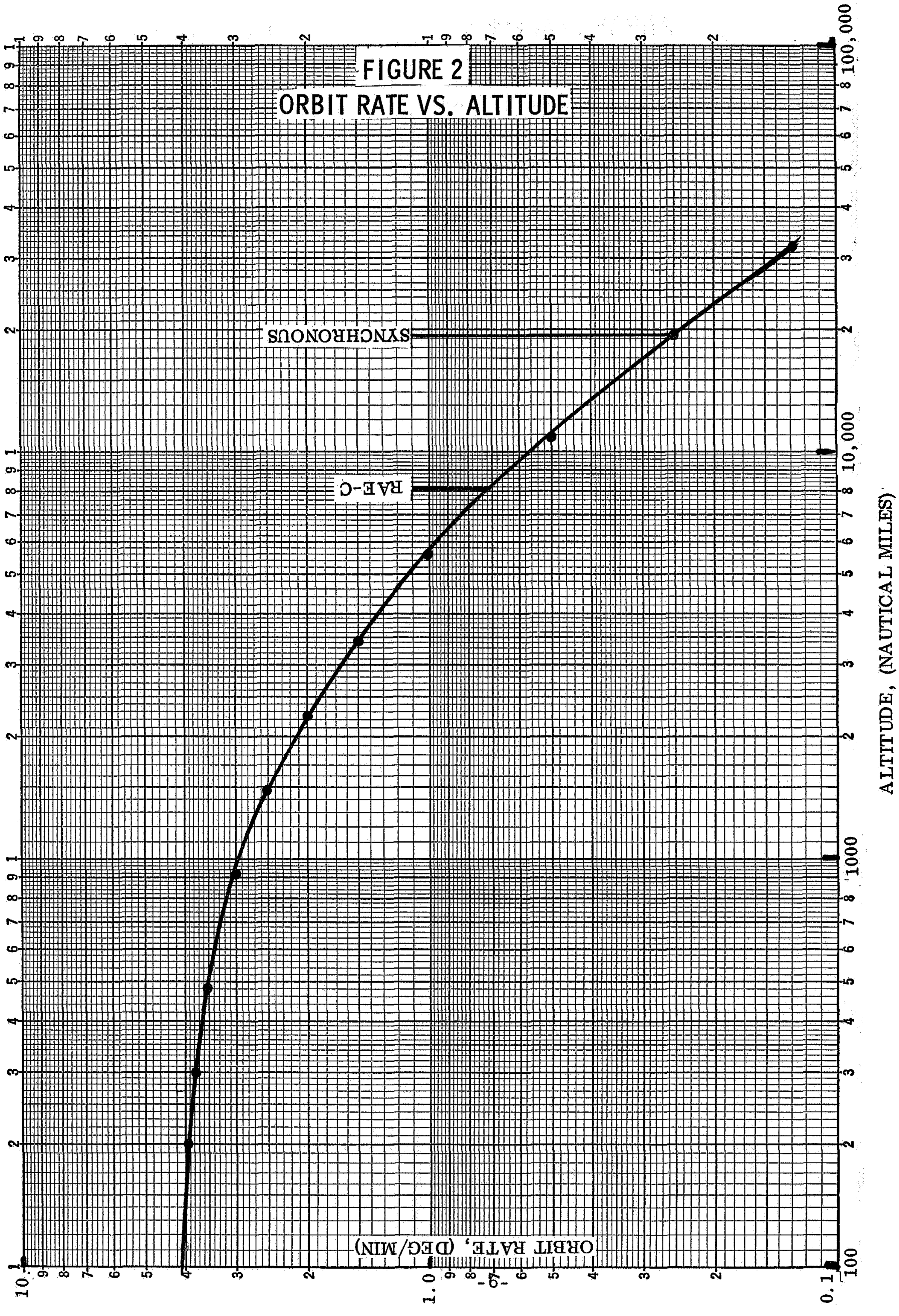


FIGURE 2
ORBIT RATE VS. ALTITUDE

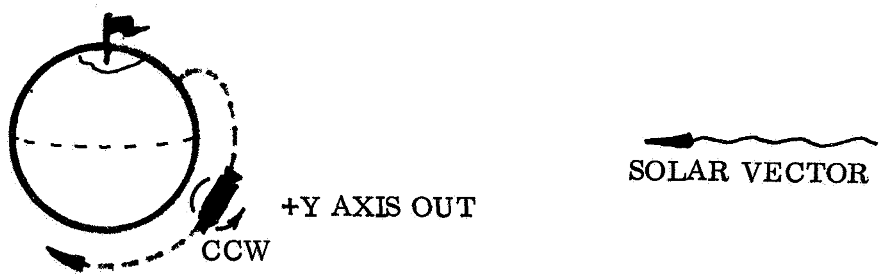
28-vdc gear reduction motors or 400-cycle and 2-kc motors are usually in a high rpm category that can impart measurable starting torques to a vehicle, due to high acceleration.

The expression $\tau = I\lambda$, torque equals moment of inertia times angular acceleration, can be restated as $\tau = I\left(\frac{\omega - \omega_o}{\tau}\right)$ in that angular acceleration (α) can be expressed as the time rate of change of angular velocity (ω), $\lambda = \frac{\omega - \omega_o}{\tau}$ where ω is final velocity and ω_o is initial velocity for a time of τ. Assuming the rotational body, a solar array in this case is initially at rest, ω_o drops out of the expression and $\frac{\omega}{\tau}$ then becomes $\frac{0.0011517}{120} \frac{\text{RAD}}{\text{sec}^2}$ where ω in radians per second relates to the previously stated fastest tracking rate of 4 deg/min.

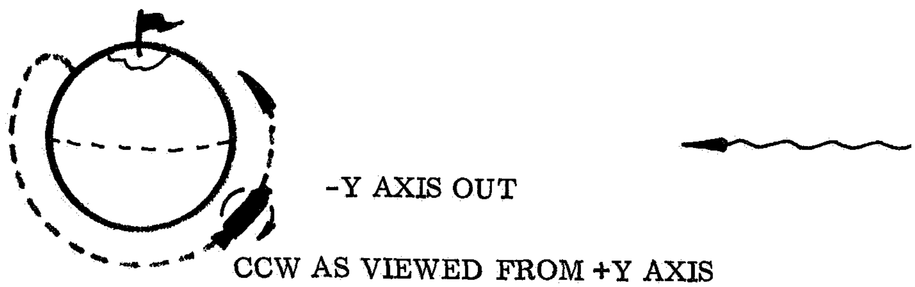
Assuming a maximum misalignment of 10 deg allowable for the array tracking accuracy, 10 deg/4 deg = 2.5 min could be allowed to make the alignment correction if the vehicle were not in motion while the correction was made. However, allowing an arbitrary 30 sec to overcome the compensatory misalignment due to vehicle continuous travel, assume as a maximum τ = 2 min or 120 sec. The initial torque expression would then be $\tau = \frac{(1)\,(0.0011517)}{120} = (I)\,(0.0000096)$. It therefore becomes apparent that such low velocities combined with long allowable misalignment correction times introduce very low required values of alignment and tracking torque to overcome array inertia. The major concern then, in that required tracking torque is so low, is to minimize the friction of the bearing techniques used in mechanizing various trackers.

The direction of tracking rotation is of interest since most thermal heliotrope concepts are unidirectional devices. Figure 3 indicates tracking directions for given launch parameters. With a daylight WTR launch, looking in on the +Y side of a three-axis stabilized earth-oriented vehicle with solar arrays tracking the sun about the pitch axis, relative rotation is counterclockwise, CCW. The vehicle moves down range into a polar type orbit. With a nighttime WTR launch the vehicle has changed position such that the viewer is looking in on the (-Y) side of the vehicle. Relative rotation appears

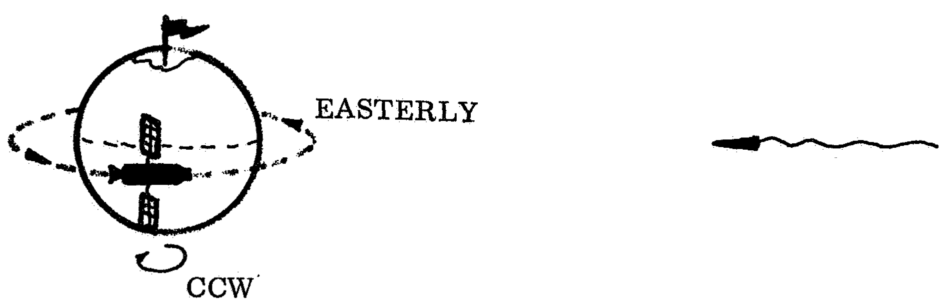
FIGURE 3
TRACKING DIRECTIONS



POLAR WTR DAYLIGHT LAUNCH



POLAR WTR NIGHT LAUNCH



EQUATORIAL ETR LAUNCH

to be CW; however, as viewed from the opposite or initial index side (+Y), rotation is still CCW. ETR launches are in an easterly direction. Looking down on the vehicle in its forward easterly direction, one again views the (-Y) side with relative motion CW but CCW as viewed from the initial index side. It has been demonstrated then that for earth-orbiting vehicles, whether in polar or equatorial orbit, a unidirectional tracking device will satisfy the major rotational requirements. This holds true for arrays in the Y-Y or pitch axis.

For twilight type orbits such as SERT II, the arrays are deployed in the X-X or line of flight axis. In this type of orbit, bidirectional adjustments may be beneficial; however, the arrays have a high effectivity (integrated projected area per rev), and it is questionable whether tracking devices would be merited for this type of application. Therefore, this study will concentrate on unidirectional thermal heliotropes. Bidirectional or gimbaled 2-axis devices other than the Alpha Adjuster should be considered for actual flight applications, depending on the specific vehicle orbit.

3. Torque Isolation

For bimetal devices in which the array is coupled directly to a bimetal helix, continuous track and reset types, the helix can act as a spring interface between the vehicle and the array to dampen array motion. The helix could function in both axial and lateral motion, isolation dependent upon the suspension clearance in the latter mode. In lateral motion the helix would function like a cantilevered beam. This concept may be especially desirable for isolating large arrays from the vehicle.

When a final specific design has been selected for the continuous tracking case, a detailed analysis will be conducted to examine torque cancellation.

4. Bearing and Interface Harnessing Techniques

With the low rotational rates associated with the sun-tracking devices, dry film lubricants are recommended. Where feasible, dissimilar materials could be applied to surfaces that are in contact. When specific concepts have reached the design phase, they will be subjected to critical review by a lubricant specialist for detail lubrication recommendations.

Models to be tested will utilize lubrication techniques compatible with the thermal vacuum environment. The conceptual models, however, do not necessarily represent prototypes of flight hardware and thus only standard precision instrument bearings will be used. There is no development effort on specific bearing techniques.

The thermal heliotrope devices are divided into two categories as far as interface harnessing is concerned. Devices that reset the solar array once per orbit may use flex harnesses for power and instrument wiring. There is a variety of standard techniques for this application. Non-array-reset devices will require slipring or commutator vehicle interfacing. Considerable information is also available on current slipring technology.

B. MISSION SELECTION

Existing missions and orbit parameters have been examined to select promising design parameters. Three mission categories have been selected and coordinate systems defined. In addition, vehicle misorientation and the possibility of two axis gimbaling have been considered.

1. Mission Categories

Three major orbit categories have been chosen as applications for thermal tracking systems: low orbit, intermediate orbit, high (synchronous) orbit.

a. Low Orbit. The altitude chosen for low orbit vehicles is 200 nm. This is representative of many NASA and Air Force low orbit mission applications. The total orbital period is 92 minutes including 36 minutes of shade time due to earth eclipse (beta zero orbit case). For low orbits, earth shade time is a considerable percentage of the total orbit as shown in Figure 4. The 200-nm orbiting vehicle is shaded up to

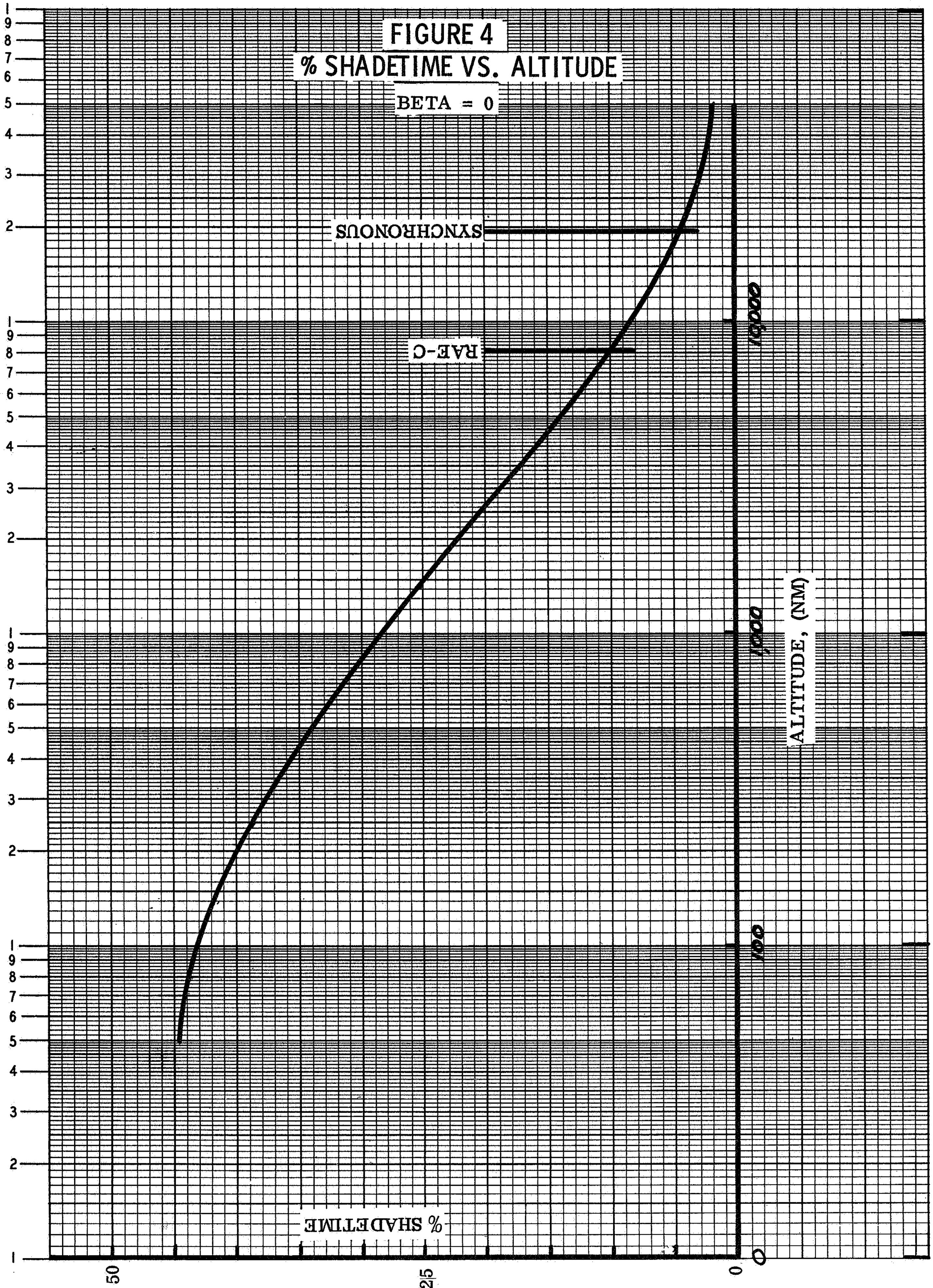


FIGURE 4
% SHADETIME VS. ALTITUDE
BETA = 0
SYNCHRONOUS
RAE-C
10,000
1000
100
0
ALTITUDE, (NM)
% SHADETIME
50
25
0

39.4 percent of the orbit period. This is assuming a collimated earth shadow parallel to the earth-sun line. Penumbra and umbra effects were studied to obtain relations for worst case earth eclipse shading (Figure 5). The effect of penumbra-umbra situation affects tracker design to a negligible extent. For example, even at a 8100-nm orbit, the angular difference between the largest umbra and penumbra is about one degree.

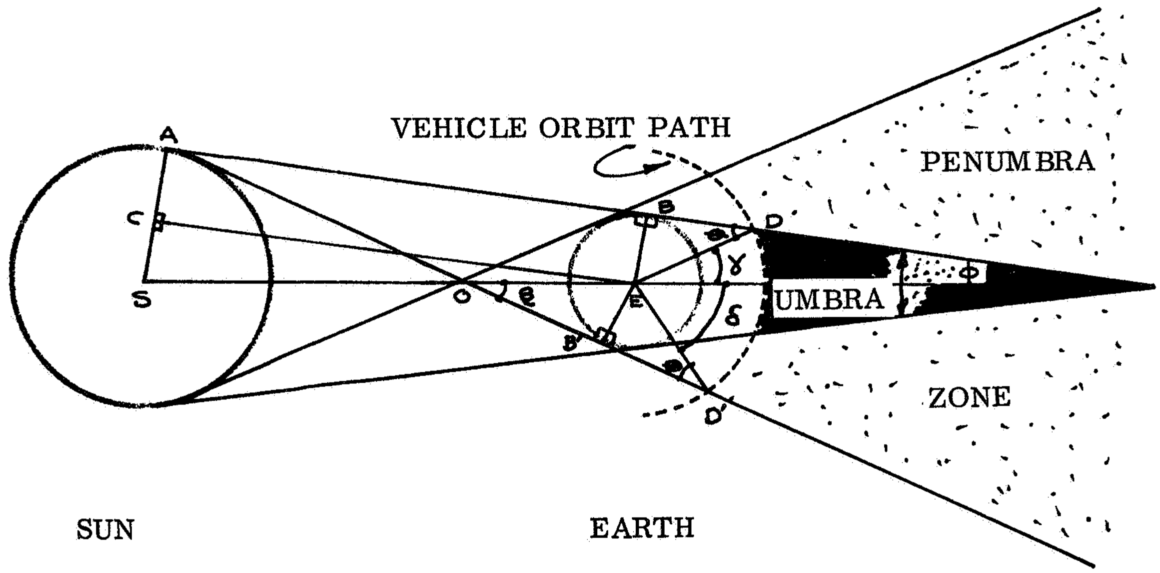
b. Intermediate Orbit. The altitude selected for intermediate orbits is 8100 nm. The proposed RAE-C vehicle will be flown at this altitude, with an equatorial inclination of 28.5 deg. Figure 6 shows that the illumination breakout angle (beta angle at which the vehicle is no longer eclipsed by the earth each orbit pass) is about 17 deg. For this particular orbit, an orbit effectivity analysis for various array tracking modes was made and the results plotted in Figure 7. It can be seen that the maximum possible beta angle for this orbit situation is 52 deg, and the minimum orbit effectivity at this point is 0.616 with a single axis tracking array. Two-axis tracking, of course, would give a unity effectivity from beta 17.3 deg to beta 52 deg. Non-tracking planer arrays with and without alpha seasonal adjust are shown for comparison.

c. High Orbit. Synchronous altitude of 19,300 nm is chosen for high altitude orbits. Most synchronous vehicles fly at low equatorial inclinations and their relatively slow orbital rate of 0.25 deg per minute makes this application especially attractive for thermal tracking devices. Figures 8 and 9 indicate synchronous altitude orbit configuration and earth eclipse duration. As shown, the orbiting vehicle is illuminated a good part of the time and no daily eclipse occurs except for certain times in the year. A thermal tracker not dependent on earth shading is necessary here.

d. Coordinate Systems Common to All Orbits. The vehicle coordinate system chosen for reference is shown in Figure 10. Most arrays will track about the Y-Y (pitch) axis. The Z axis is always toward the earth's local vertical.

The major celestial source of reference for thermal heliotrope devices is the sun. With photovoltaic power systems, the orbited body-sun line becomes the most important celestial coordinate, regardless of which solar system body the vehicle is orbiting – Earth, Moon, Mars, etc. In the case of a sun-orbiting vehicle, the significant coordinate

FIGURE 5
EARTH ECLIPSE DURATION



UMBRA VERTEX HALF ANGLE $\Big\}$ $\phi = SIN^{-1} \dfrac{SC}{SE} = SIN^{-1} \dfrac{(SA-EB)}{SE}$

VEHICLE SHADE HALF ANGLE IN UMBRA $\Big\}$ $\gamma = \theta - \phi = SIN^{-1} \dfrac{EB}{ED} = SIN^{-1} \dfrac{(SA-EB)}{SE}$

$$2\gamma = 2\left(SIN^{-1} \frac{R_E}{R_V} - SIN^{-1} \frac{(R_S - R_E)}{D}\right)$$

TOTAL DWELL ANGLE IN UMBRA ZONE

R_S = SUN RADIUS
R_E = EARTH RADIUS
R_V = VEHICLE ORBIT RADIUS
D = EARTH-SUN DISTANCE

$\dfrac{EB'}{SA} = \dfrac{EO}{SO}$, $SO = SE - EO$, $\therefore$ $\dfrac{EB'}{SA} = \dfrac{EO}{(SE-EO)}$

$SA(EO) = EB'(SE) - EB'(EO)$

$EO(SA+EB') = EB'(SE)$

$EO = \dfrac{EB'(SE)}{(SA+EB')}$

PENUMBRA VERTEX HALF ANGLE $\Big\}$ $\beta = SIN^{-1} \dfrac{EB'}{EO} = SIN^{-1} \dfrac{EB'(SA+EB')}{EB'(SE)} = SIN^{-1} \dfrac{(SA+EB')}{SE}$

VEHICLE SHADE HALF ANGLE IN PENUMBRA $\Big\}$ $\delta = \theta + \beta = SIN^{-1} \dfrac{EB'}{ED'} - SIN^{-1} \dfrac{(SA+EB')}{SE}$

$$2\delta = 2\left(SIN^{-1} \frac{R_E}{R_V} + SIN^{-1} \frac{(R_S + R_E)}{D}\right)$$

TOTAL DWELL ANGLE IN PENUMBRA ZONE

FIGURE 6
ILLUMINATION LIMIT ANGLE

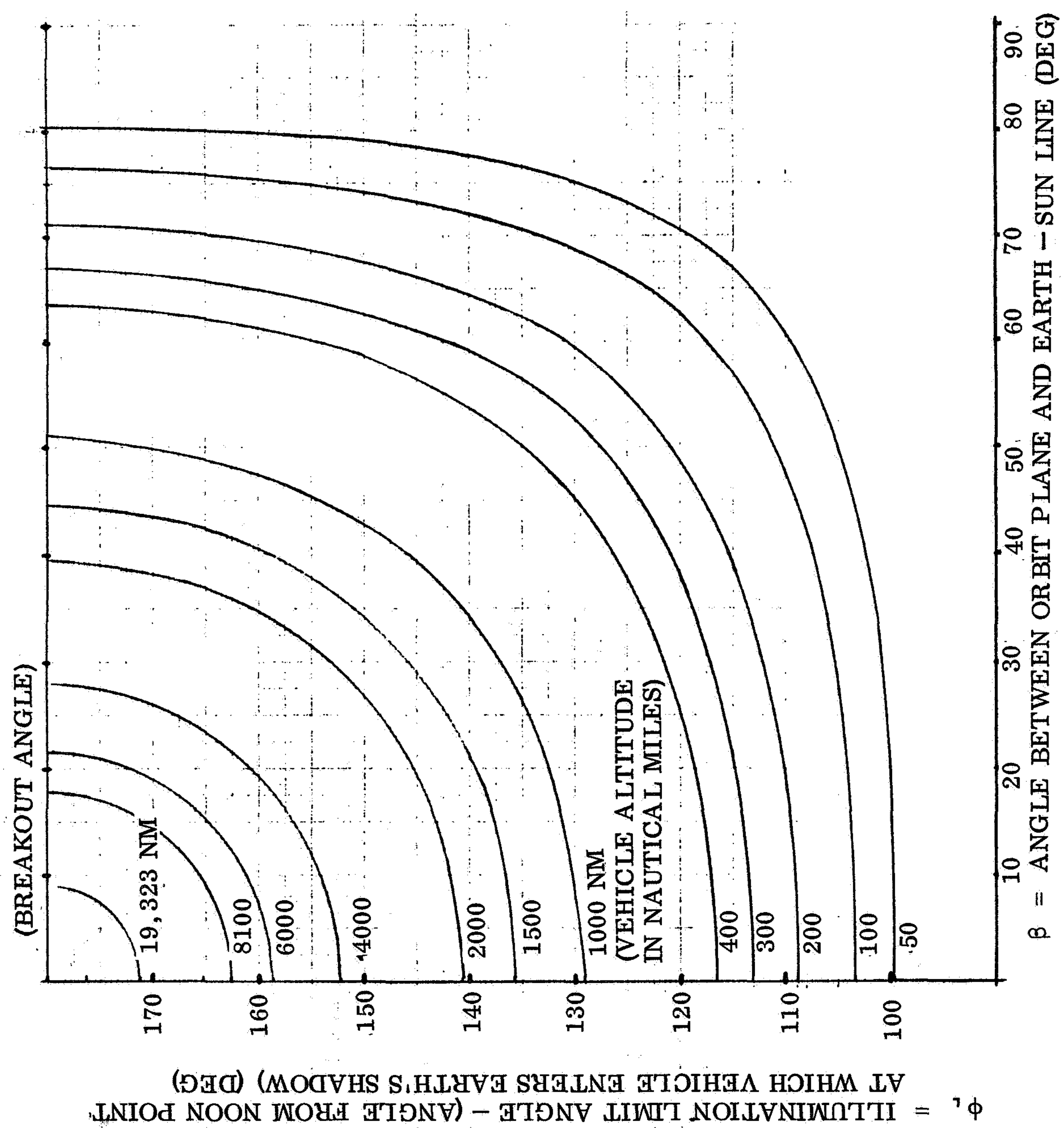


FIGURE 7
EFFECTIVITY VS. BETA ANGLE
8100 NM

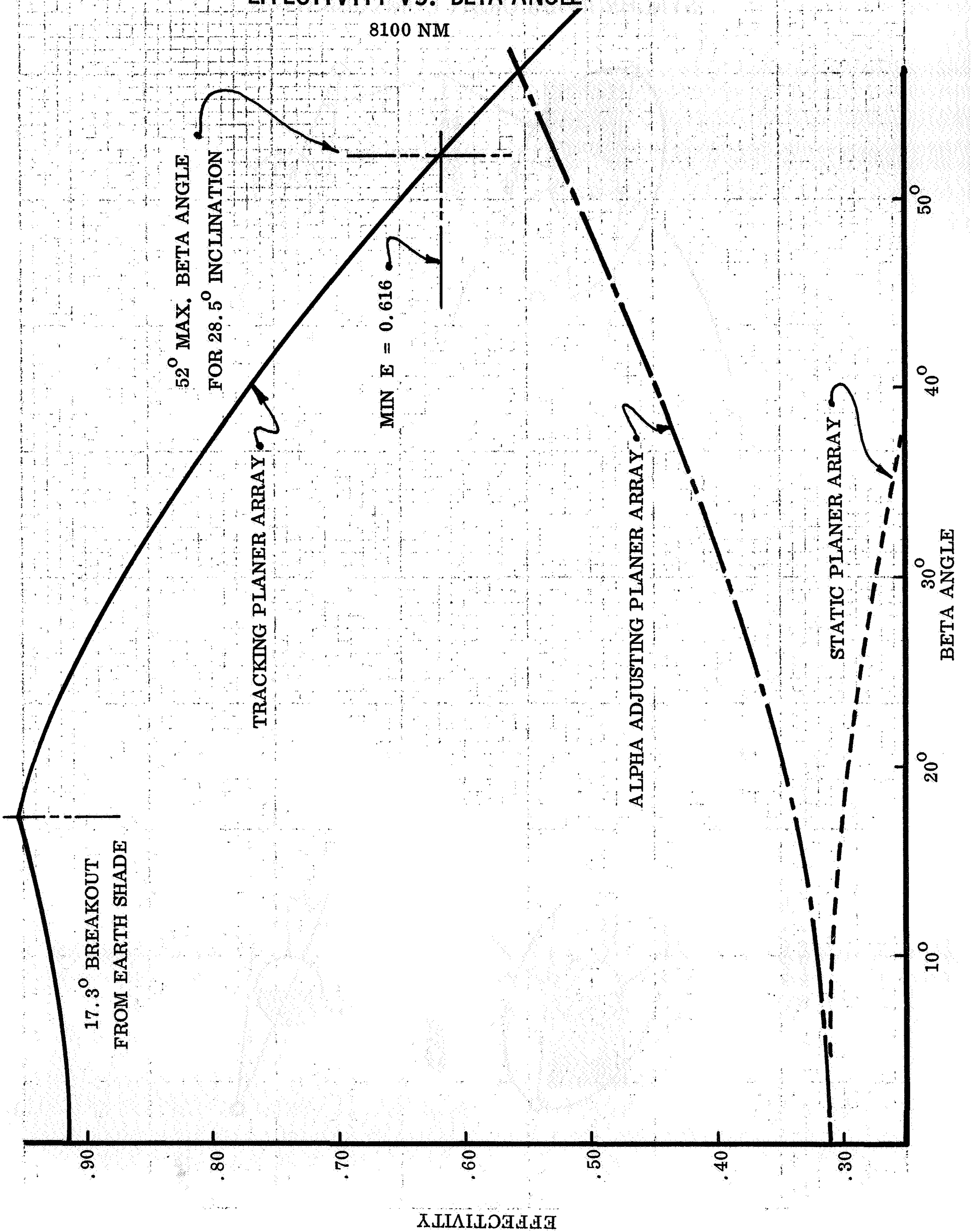
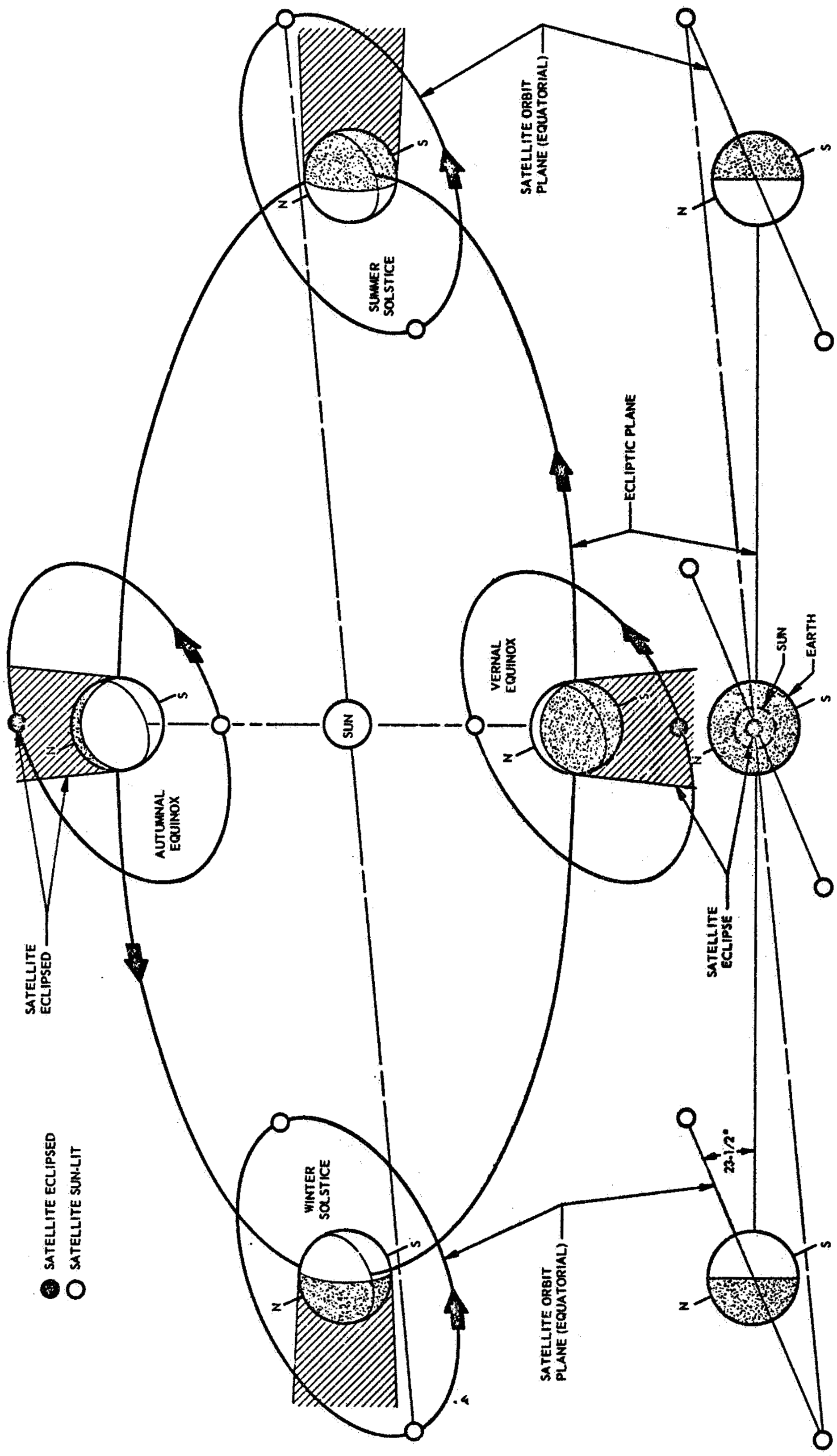
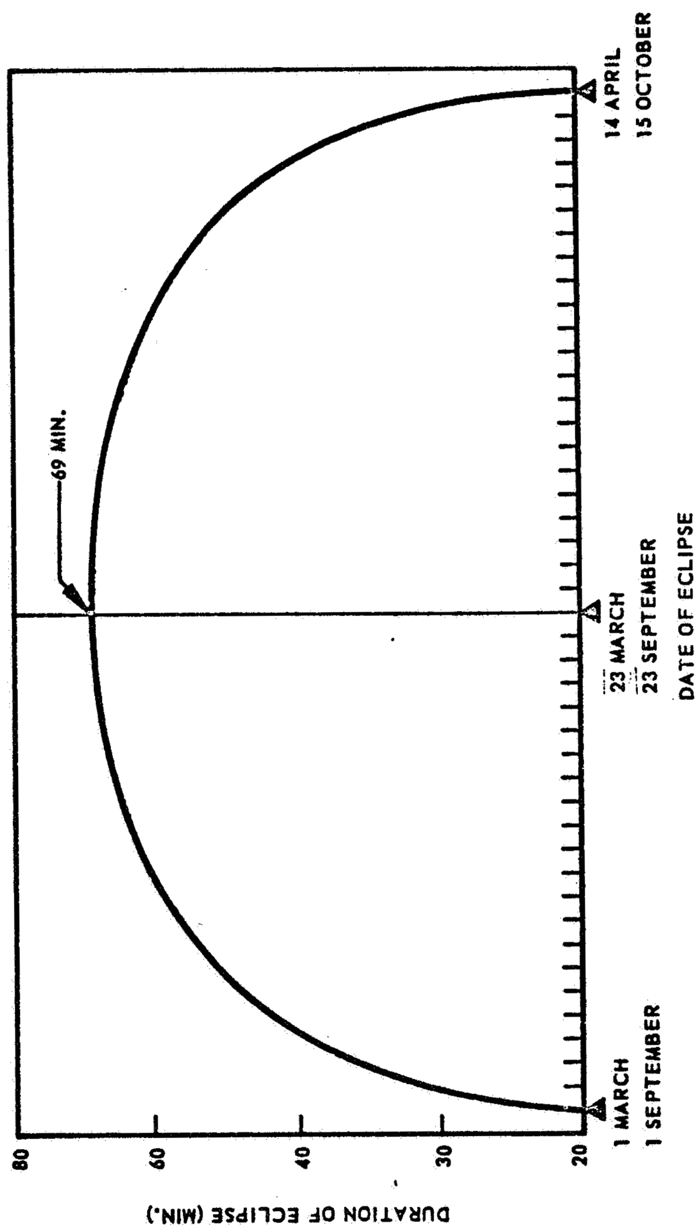


FIGURE 8
SYNCHRONOUS ORBIT CONFIGURATION



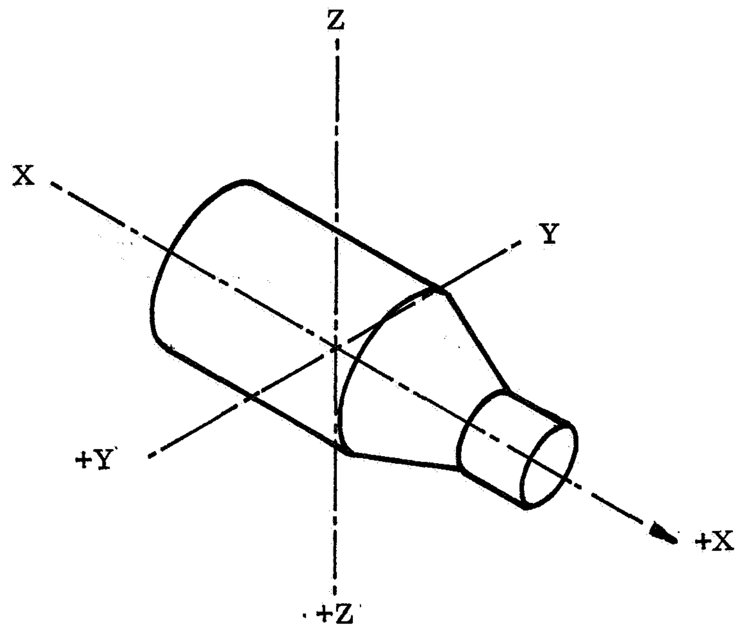
Synchronous Orbit Eclipse (Once Each Day for 43 Days in Spring and Fall)

FIGURE 9
SYNCHRONOUS ECLIPSE DURATION



Eclipse Duration/Date

FIGURE 10
VEHICLE COORDINATE SYSTEM



AXIS

X-X AXIS	Line of flight or roll axis with +X the forward direction.
Z-Z AXIS	Axis coincident with local vertical or yaw axis with +Z towards the orbited body.
Y-Y AXIS	Mutually perpendicular or pitch axis with +Y to the left with +X viewed as a head on point.

MANEUVERS

Positive Roll	CCW with +X viewed as a point in the Y-Z plane.
Positive Pitch	CCW with +Y viewed as a point in the X-Z plane.
Positive Yaw	CCW with +Z viewed as a point in the Y-X plane.

(Negative is CW in all cases)

system for an earth-orbiting vehicle. A primary reference is the minimum included angle between the orbit plane and the earth-sun line. This angle is designated as the beta (β) angle.

To aid in defining the vehicle position in orbit, it is necessary to establish another primary reference point. The point is called the noon point (NP) and is the point nearest the sun at which the vehicle passes through the earth-sun orbital plane (ecliptic plane). For a $\beta = 90^o$ twilight orbit, this point will be the point in vehicle orbit which is, on ecliptic passthrough, trailing in relation to the earth's CCW direction about the sun. When the vehicle orbit plane is coincident with the earth-sun line ($\beta = 0^o$), the NP is the point in vehicle orbit nearest the sun. The angle ϕ is measured from the NP to the vehicle. The illumination set back angle (Figure 11) is ϕL ; it is also the angle between earth shading and the NP.

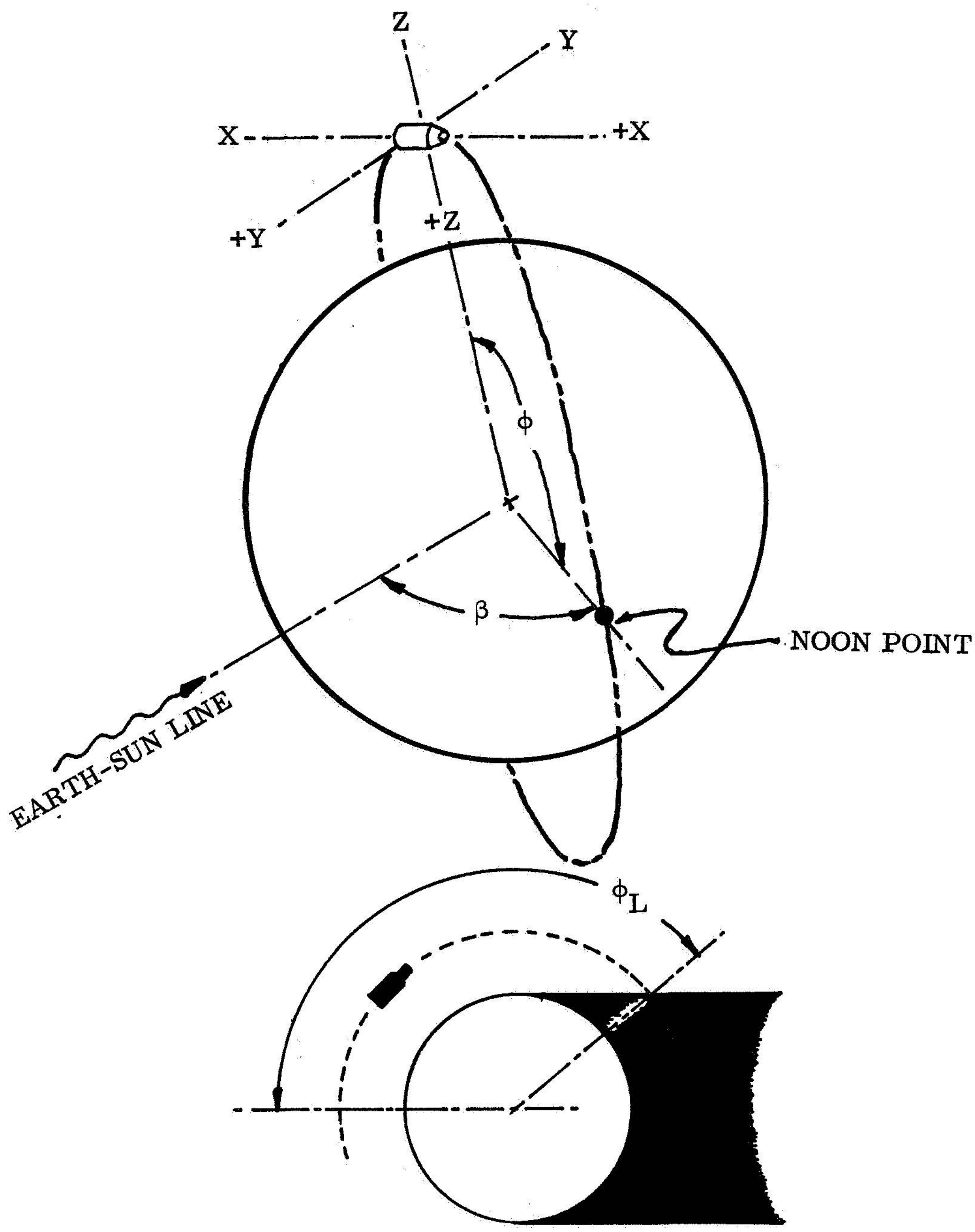
From these coordinates or references and the vehicle coordinate system, one can define the location and relative motion of a solar array as positioned by the thermal heliotrope.

2. Vehicle Misorientation and Two Axis Gimbaling

Vehicles that use tracking solar arrays are normally three-axis stabilized. If vehicle instability occurs, it may be cyclical, slow rate, and of such minor excursion that no appreciable effect occurs on the tracking system. However, many modes of random motion, tumbling about the pitch axis, yaw or roll motions could completely invalidate the uniform power production of a tracking solar array system. A great variety of vehicle configurations containing diverse types of guidance and control systems have been flown. It is out of scope of this contract to make a detailed evaluation of array tracking system response as a function of vehicle instability. However, when specific vehicle applications are considered, productive analysis could occur in this interaction area. Task I therefore assumes vehicle stability but with initial orbit inject misorientation.

One full two-axis tracking system has been developed and qualified for space use by Lockheed. Another system – developed, qualified, and flown – used single axis tracking

FIGURE 11
ORBIT COORDINATE SYSTEM



β = Angle between earth-sun line and orbit plane

NP = noon point —— point in orbit path nearest the sun

ϕ_L = Illumination set back angle; angle between noon point and point at which vehicle enters earth shade with a secondary axis adjust. The former system was designated the "zombie" system and used d-c torquers for continuous tracking with sliprings for sensor and power transfer. The zombie system was considered for use on the aft rack of an Agena vehicle, deployed on a telescoping boom in such a way that adequate displacement avoided interference of the arrays with vehicle structure. It also rendered the system more operative by minimizing shadowing and view factor interference. It is significant that a two axis system requires more physical separation from the vehicle than does a single axis system. Also, power transfer methods would be more complex and dynamic interaction with the vehicle may be increased. Investigation of two-axis thermal heliotrope tracking systems will be confined to evaluating conceptual design approaches for implementing bidirectional, two-axis bimetal devices.

C. BIMETALS AS WORK PRODUCING ELEMENTS

Bimetals, or thermally active metal couples, may be used as work producing elements. The following section explains: (a) the general bimetal theory and (b) the application of this basic theory to sun-tracking devices. Bimetal couple construction, principles of operation, and the basic deflection formula are covered. Specific formulas for configured elements and particular design parameters are discussed under basic applications.

1. General Bimetal Theory

a. Bimetal Construction. Bimetal is a term used for a sandwich of thermostatic metals. Although the bimetal term indicates two metals, many sandwiches consist of three layers of metal. The ASTM definition of thermostat metal (hereafter called bimetal) is "a composite material, usually in the form of sheet or strip, comprising two or more materials of any appropriate nature, metallic or otherwise, which, by virtue of differing expansivities of the components tends to alter its curvature when its temperature is changed."

There are four main methods of bonding the metal components into a sandwich; in brief, they are explained below:

- Puddle bonding consists of casting one alloy onto another heated but solid alloy.
- Hot roll bonding is a hot rolling mill operation often at temperatures above $2000^{o}F$ and moderate pressures. The material enters the mill in bar form with the edges welded to prevent contamination and separation. The actual bond is made on the first pass through the mill and improved on further passes.
- Pressure-temperature bonding is a similar operation except that the material enters the mill cold, and heat is generated by the high reduction. The bond is created in one pass and improved by a sintering operation.
- Press bonding is a high temperature and pressure static press bond.

b. Principles of Operation. The principle of bimetalic deflection depends on a difference in thermal expansion coefficients between the components. For example, a basic bimetal couple is shown in Figure 12a. The two elements are identical in size but the upper one has a coefficient of thermal expansion, δ, larger than that of the bottom. An increase in temperature will cause both components to increase in length with the top trying to expand more than the bottom. The top component will be prevented from expanding to its free length and will be under a compressive stress developed at the bond line. Conversely, the bottom component will be stretched and will be under a tensile stress at the bond line. The two stresses are equal and uniform along the length of the components. Figure 12b is a stress diagram of the bimetal couple. The stresses may be replaced by a resultant torque at each end. It can be seen then that the couple will bend into an arc of radius R. For equal component thicknesses and moduli of elasticity, the bond line stress is (Ref. 1):

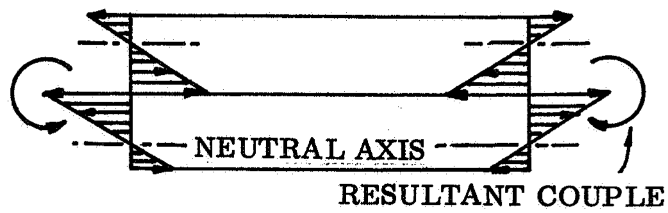
$$S = \frac{E}{2}(\delta_1 - \delta_2)\,\Delta T$$

The stress at the extreme fibers is half of this and in the opposite direction (Figure 12b). The high expansion component is in compression at the bond and in tension at the extreme fibers. The converse is true of the low expansion component. The neutral axis in thermal bending is one-third the distance from the extreme fiber to the bond line.

FIGURE 12
BIMETAL THEORY

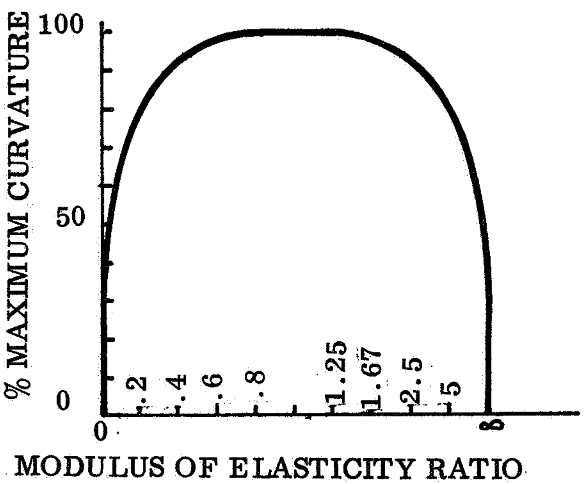
BIMETAL SANDWICH

(a)

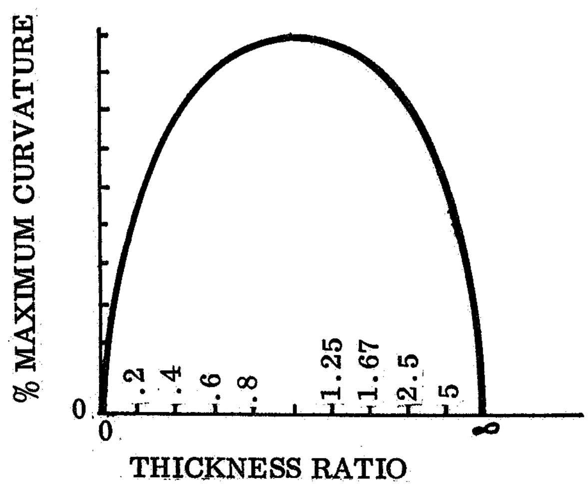


STRESS DIAGRAM

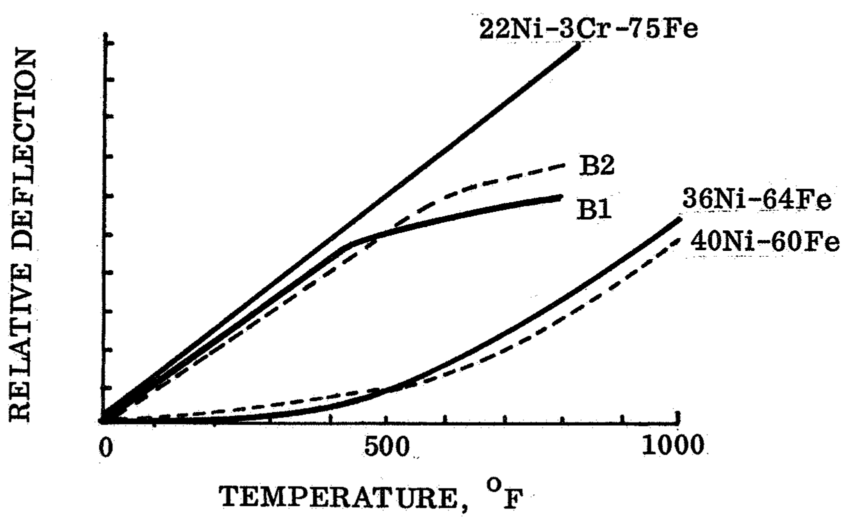
(b)



(c)



(d)



(e)

c. <u>Basic Deflection Formula.</u> The basic deflection formula for a bimetal couple was developed by Timoshenko in 1925 and is (Refs. 2, 3):

$$\frac{1}{R} = \frac{6\,(\Delta\delta)\,(\Delta T)\,(1+m)^2}{t\left[3\,(1+m)^2 + (1+mn)\,(m^2 + \frac{1}{mn})\right]}$$

where:

t = total component thickness

$m = \frac{a_1}{a_2}$ = ratio of thickness

$n = \frac{E_1}{E_2}$ = ratio of moduli of elasticity

R = radius of curvature at bond line

$\Delta\delta$ = difference in component expansion coefficients

ΔT = temperature change

It can be readily seen that the deflection is increased by larger $\Delta\delta$ and ΔT values and a lower material thickness. Not so obvious is the effect of the n and m ratios. By setting all the values in the preceding equation to unity except n, the expression becomes (Ref. 1):

$$\frac{1}{R} = \frac{24\,n}{(n^2 + 14n + 1)}$$

Differentiating $1/R$ with respect to n gives a maximum curvature value at $n = 1$ of 1.5. Dividing by 1.5 and multiplying by 100 gives the percent of maximum curvature.

$$\%\ \text{max curvature} = \frac{1600\,n}{(n^2 + 14n + 1)}$$

This expression is plotted in Figure 12c. The curve shows that for maximum curvature the n ratio should be unity; however, since the curve is flat topped, even using E values as different as 15×10^6 psi and 30×10^6 psi gives 97 percent of the maximum curvature. This value can be increased to 100 percent by varying the component thickness as below:

$$\frac{a_1}{a_2} = \frac{\sqrt{E_2}}{\sqrt{E_1}}$$

To investigate the ratio of thicknesses (m) alone, all terms in Timoshenko's formula are set to unity except m yielding:

$$\frac{1}{R} = \frac{6\,m}{(1 + m^2)}$$

Manipulating as before yields:

$$\%\ \text{max curvature} = \frac{400\ m}{(1 + m^2)}$$

This expression is plotted in Figure 12d. This curve has a relative sharp peak at $n = 1$ indicating the importance of accurate control of thickness ratios.

Timoshenko's formula is also affected by the fact that the so-called linear coefficient of thermal expansion, δ , is not actually linear. Figure 12e illustrates this point. The 22 Ni-3Cr-75Fe alloy has essentially a linear relative expansion in the temperature range shown; however, most alloys do not, as illustrated by the 36 Ni-64Fe (invar) curve. Bonding the 36 Ni alloy to the 22 Ni alloy gives a bimetal indicated by B1 that looses its linearity at about $400^{\circ}F$. In nickel-iron alloys the temperature at which the inflection point occurs (point at which expansion rate starts to increase) starts to increase with nickel alloys over about 36 Ni. Also with high Ni alloys the low temperature expansion is greater. The result of these two factors is a crossing of the curves as shown on the 36 Ni and 40 Ni alloys. A similar crossing is evident when these alloys are bonded to a linear alloy as shown by bimetal curves B1 and B2. To allow for the change in δ with temperature bimetal equations, a variable called flexivity is used. It is defined by the formula (Ref. 4)

$$F = \frac{3\,(\Delta\delta)}{2}$$

and is a standard ASTM term. Flexivity envelopes for the range of bimetals are shown in Figure 13. Manufacturers often supply plots of flexivity vs. temperature for any particular type of bimetal. These plots are determined empirically and apply to trimetal systems also. A wide variety of bimetal materials is available. Figure 14 shows many of the bimetals and gives some of the properties discussed in the preceding paragraphs.

2. Application to Sun-Tracking Devices

Bimetal elements may be configured in many shapes. In general, all can be subdivided into three categories: coils, strip elements, and formed parts. Coil elements are used when the required deflection (or rotation in the case of a sun-tracking device) is relatively large. Strips and formed parts are more appropriately used as sensors or snap devices. In the following sections specific coil formulas (a) and bimetal work (b) will be discussed.

a. Coil Formulas. Bimetal coils may be wound in the form of a spiral or helix. Since sun tracking requires maximum exposed area for heating and cooling, only helixes will be discussed here (the governing formulas are nearly the same). There are three main equations for designing helical bimetals; they are:

$$\text{thermal deflection} = A = \frac{67\,F\,(\Delta T)\,L}{t}$$

$$\text{mechanical torque} = \Gamma = \frac{0.0232\ EA\ wt^3}{L}$$

$$\text{thermal torque} = \Gamma = 1.55\ EF\,(\Delta T)\,wt^2$$

FIGURE 13
FLEXIVITY ENVELOPES FOR BIMETALS

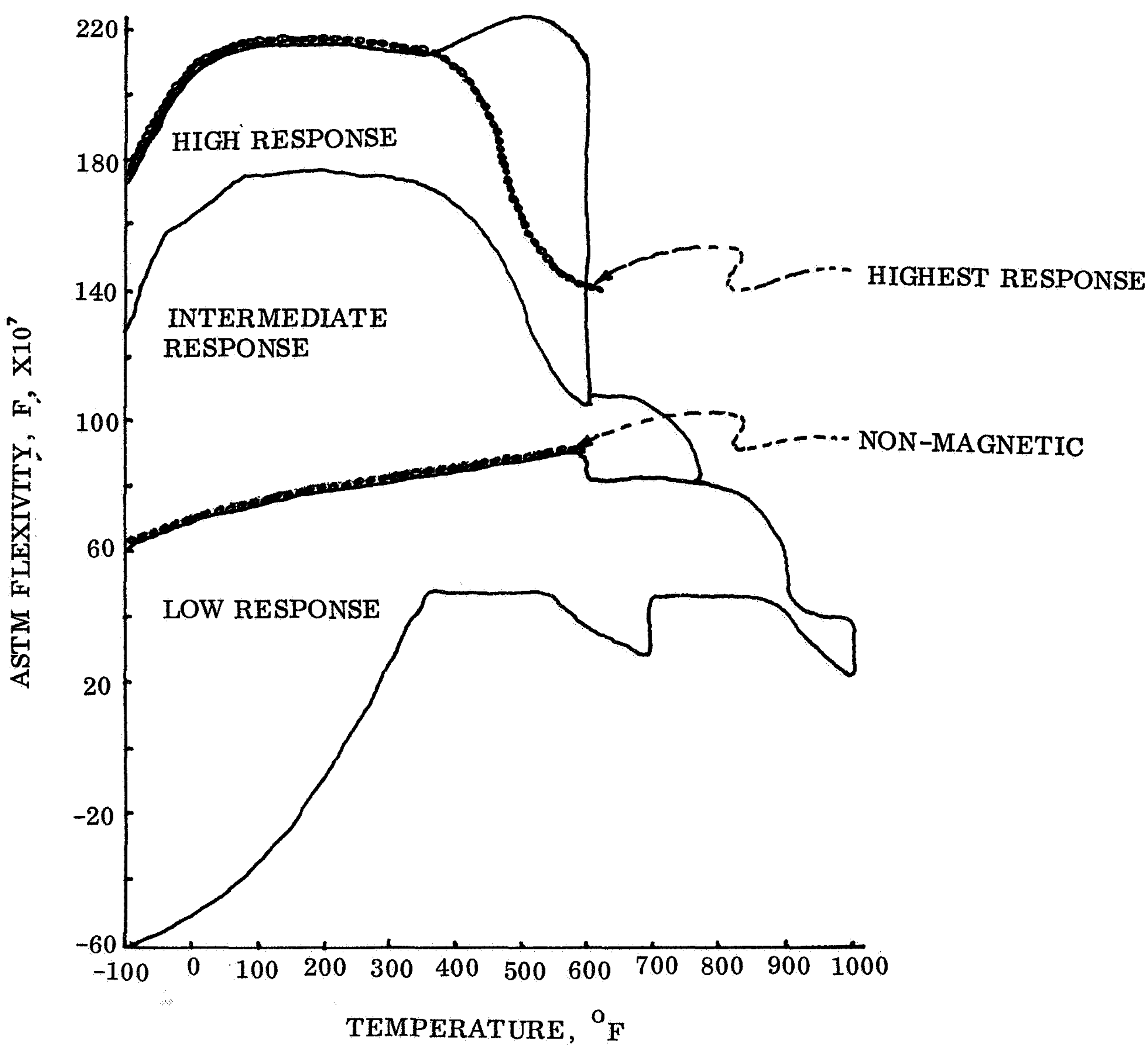


FIGURE 14
COMPONENTS OF "BIMETAL" ELEMENTS

"TRUFLEX" TYPE	HIGH SIDE		INTERMEDIATE		LOW SIDE	
	ALLOY	PER CENT BY THICKNESS	ALLOY	PER CENT BY THICKNESS	ALLOY	PER CENT BY THICKNESS
A1	A	55			10	45
AG1	AG	50			10	50
B1	B	50			10	50
B2	B	50			20	50
B3	B	50			30	50
B11	B	50			11	50
BN	B	50			N	50
B100R	B	28	N	44	10	28
B125R	B	34	N	32	10	34
B150R	B	36	N	28	10	36
B175R	B	39.5	N	21	10	39.5
B200R	B	42	N	16	10	42
B250R	B	44.5	N	11	10	44.5
B300R	B	47	N	6	10	47
B350R	B	48	N	4	10	48
B400R	B	49	N	2	10	49
C1	C	50			10	50
C3	C	50			30	50
C11	C	50			11	50
D560R	D	50			10	50
E1	E	50			10	50
E3	E	50			30	50
E4	E	50			40	50
E5	E	50			50	50
EN5	E	47.5	N	5	50	47.5
F1	F	63			10	37
F15R	B	5	F	80	10	15
F20R	B	5	F	60	10	35
F25R	B	10	F	50	10	40
F30R	B	20	F	40	10	40
F35R	B	24	F	36	10	40
F40R	B	29	F	31	10	40
F50R	B	25	F	25	10	50
F60R	B	32	F	18	10	50
F70R	B	34	F	16	10	50
F90R	B	38	F	12	10	50
F100R	B	40	F	10	10	50
G1	G	50			10	50
G3	G	50			30	50
G7	G	50			70	50
GA12	GA	50			12	50
GB-14	GB	50			14	50
H1	H	50			10	50
J1	J	55			10	45
J7	J	55			70	45
J8	J	55			80	45
K1	K	50			10	50
L1	L	50			10	50
M7	M	50			70	50
M8	M	50			80	50
MB18	B	47	†	†	10	47
N1	N	50			10	50
NF4	N	35	F	30	40	35
P3	P	54			30	46
P675R	P	55			10	45
P850R	P	80			10	20
PJ	F	50			J	50
R2	R	50			20	50
1513	15	50			13	50
7110	71	50			10	50

†Clad with 3% of Alloy M on HES and 3% of Alloy 80 on LES

ALLOY ANALYSIS

A – 62 Cu, 38 Zn (Brass)
AG – Pure Silver
B – 22 Ni, 3 Cr, Bal Fe
C – 19.4 Ni, 2.25 Cr 0.5C Bal Fe
D – 14.65 Ni, 9.5 Mn, 5.1 Al, Bal Fe
E – 25 Ni, 8.5 Cr, Bal Fe
F – 98 Cu, 2 Ag
G – 18 Ni, 11.5 Cr, Bal Fe
GA – 18 Ni, 10 Cr, 3 Mo, Bal Fe
GB – 19 Ni, 7 Cr, Bal Fe
H – 14 Ni, 5 Mn, 0.5C Bal Fe
J – 1.50 Si, 0.3 Mn, Bal Cu (Silicon Bronze)
K – Armco Iron
L – 25 Ni, 4 Mn, Bal Fe
M – 18 Cr, 8 Ni, Bal Fe
N – Pure Nickel
P – 72 Mn. 18 Cu. 10 Ni
R – 66.5 Ni, 1.5 Fe, 1.0 Mn 31 Cu (B Monel)
10 – 36 Ni, 64 Fe (Invar)
11 – 38.65 Ni, Bal Fe
12 – 31 Ni, 8 Cr, 8 Co, Bal Fe
13 – 32 Ni, 15 Co, 1 Mo, Bal Fe
14 – 38 Ni, 7 Cr, Bal Fe
15 – 32 Ni, 1 Co, 1 Mo, Bal Fe
20 – 40 Ni, Bal Fe
30 – 42 Ni, Bal Fe
40 – 45 Ni, Bal Fe
50 – 50 Ni, Bal Fe
70 – 17 Cr, Bal Fe (Type 430 stainless iron)
71 – 16.5 Cr, 4.5 Al, Bal Fe
80 – 57 Co, 9 Cr, Bal Fe

Courtesy of Metals and Controls, Inc., Division of Texas Instruments, Inc.

where:

A = rotation (degrees)

F = ASTM flexivity

Γ = torque (in.-oz)

E = equivalent modulus of elasticity (psi)

ΔT = temperature change (^oF)

w = stock width (in.)

t = stock thickness (in.)

L = stock length (in.)

In the thermal deflection formula, A is the angle of unrestrained rotation for a given coil subjected to ΔT. The mechanical torque formula gives torque in in.-oz produced by rotating one end of a coil an angle of A. The thermal torque formula states the total torque available from a given coil subjected to ΔT.

The value of E used in bimetal equations is an equivalent modulus of elasticity (Ref. 1). The expression is:

$$E = \frac{4E_1}{t^3}\left[(a_1 - C_1)^3 + C_1^3 + \frac{E_2}{E_1}\left\{(a_1 + a_2 - C_1)^3 - (a_1 - C_1)^3\right\}\right]$$

where

$$C_1 = \frac{E_1 a_1^2 + E_2 a_2 (2a_1 + a_2)}{2(E_1 a_1 + E_2 t_2)}$$

and if

$$\frac{a_1}{a_2} = \left(\frac{E_2}{E_1}\right)^{1/2} \quad \text{for maximum deflection}$$

then

$$E = \frac{4E_1\, a_1^{\,3} + 4\,E_2\, a_2^{\,3}}{t^3}$$

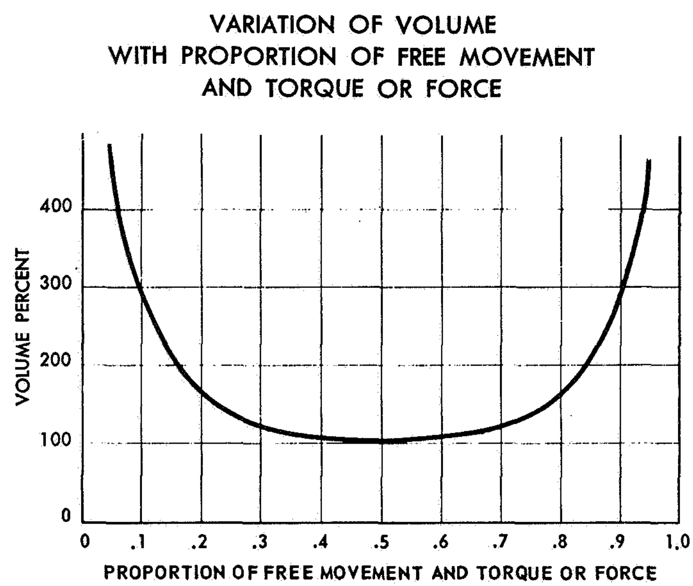
For a given operating temperature range, a flexivity value is obtained from manufacturer's empirical data. The formulas can then be used for prediction of bimetal coil performance.

b. Bimetal Work. Since sun tracking requires that work be generated by the bimetal element, maximum work elements are desirable. Alban (Ref. 4) has shown that a coil configuration will produce approximately 50 percent more work than a cantilever-mounted straight strip of the same volume. In addition, using a coil configuration negates the problem of converting linear to rotary motion. Adding to the effectiveness of helical coils is the fact that all motion is confined to producing the desired rotating motion. For example, a rectangular cantilever-mounted strip will tend to deflect in all directions. The major curvature will occur about the width axis. Deflection about the length axis will tend to reduce the former curvature. Crimping the element will help restrain the length axis deflection and restore ideal curvature. A helical coil, however, naturally restrains the length axis deflection by means of its curved shape. Thus, no crimping is necessary to ensure maximum rotation.

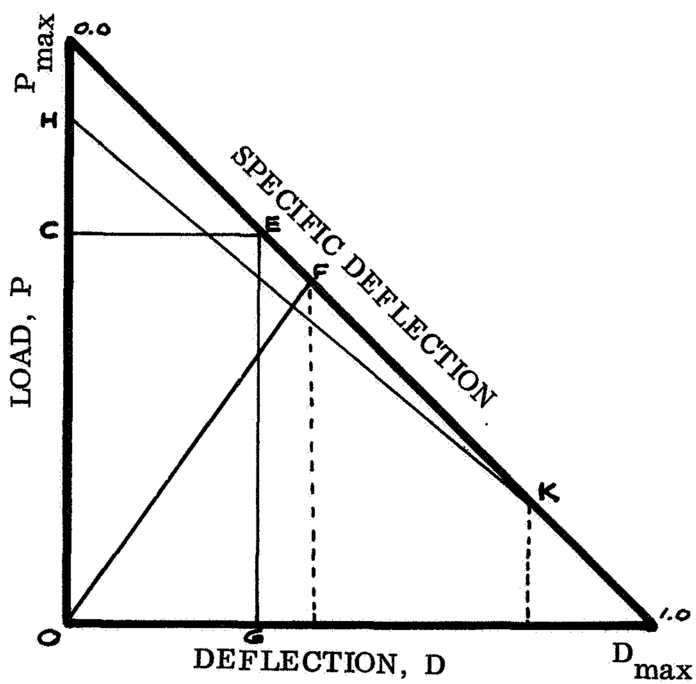
Maximum work is obtained by allowing half the bimetal temperature change to produce deflection and half to produce force or torque. Figure 15a shows the relation between the deflection/force ratio and volume for a bimetal element. Two factors should be noted here. First, the curve is relatively flat on the bottom, thus relaxing the need for a ratio of exactly 0.5 . Second, the bimetal coil in an actual tracking device is a small part of the total system weight, so volume penalties are not of major consideration.

Figure 15b is a plot of load vs. deflection for bimetals. For any temperature change, the final operating condition of the bimetal can be represented by a point on the diagonal line. Three work cases exist related to this curve. If a bimetal develops a

FIGURE 15
BIMETAL WORK



(a)



(b)

load and then displaces (overcoming a detent or snap device operation), the work path is OCE. Conversely, if an element deflects and then produces a force with no further movement, the path is OGE. A constant-rate spring load produces a work path of OF. The area under these paths is work, and it is evident that maximum ideal work is obtained by operating at a specific deflection point of 0.5 through a rectangular path. However, by combining the above cases, a larger work area is possible, as shown by path OHK. Here force is restrained until a detent releases at H, at which point decreasing load of friction and inertia is carried to deflection point K. It can be seen that the work indicated under this path is higher than the so-called maximum work point.

As delivered by the manufacturer, the bimetal element stock itself is optimized for maximum performance. The thickness ratio has been matched to modulus of elasticity ratio as previously described. In order to maximize performance of thermal heliotrope devices, tradeoffs are necessary between maximum available torque and thermal response (discussed in Thermal Analysis section). Snap acting devices, however, appear to have the greatest promise in meeting the previously discussed optimal bimetal design parameters.

D. THERMAL ANALYSIS

Utilization of helical bimetal coils in sun-tracking systems involves radiative heating and cooling of the coil material in order to produce temperature changes necessary for tracking motions. It is desirable in most cases to have a relatively high thermal response coil; that is, one which will heat and cool quickly. To this end an analysis of thermal performance is being performed. Results to date are summarized here.

1. Thermal Mass

Thermal mass is directly proportional to stock thickness, t :

M = coil mass = $w t L \rho$

A_t = total exposed area = wL

$$A_p = \text{projected area} = \frac{w\,L}{\pi}$$

$$\text{thermal mass} = \frac{M\,C}{A_e} = \frac{w\,t\,L\rho c}{WL} = \rho c\,(t)$$

In order to maximize thermal response, a low thermal mass element is necessary. It should be noted, however, that the torque producing capability of the coil is proportional to the square of coil thickness. A compromise must be made between response and torque capability. Sizing t near to the required minimum response is the design method. Torque capability can then be increased by increasing coil stock width or multiplication devices (see Auxiliary Devices section).

2. Equilibrium Temperature

Upper equilibrium temperature is proportional to $(\frac{\alpha}{E})^{1/4}$

$$Q_i = \text{heat in} = \alpha S\ A_p$$

$$Q_o = \text{heat out} = \varepsilon\,\sigma\,A_t\,(T_c^{\ 4} - T_s^{\ 4})$$

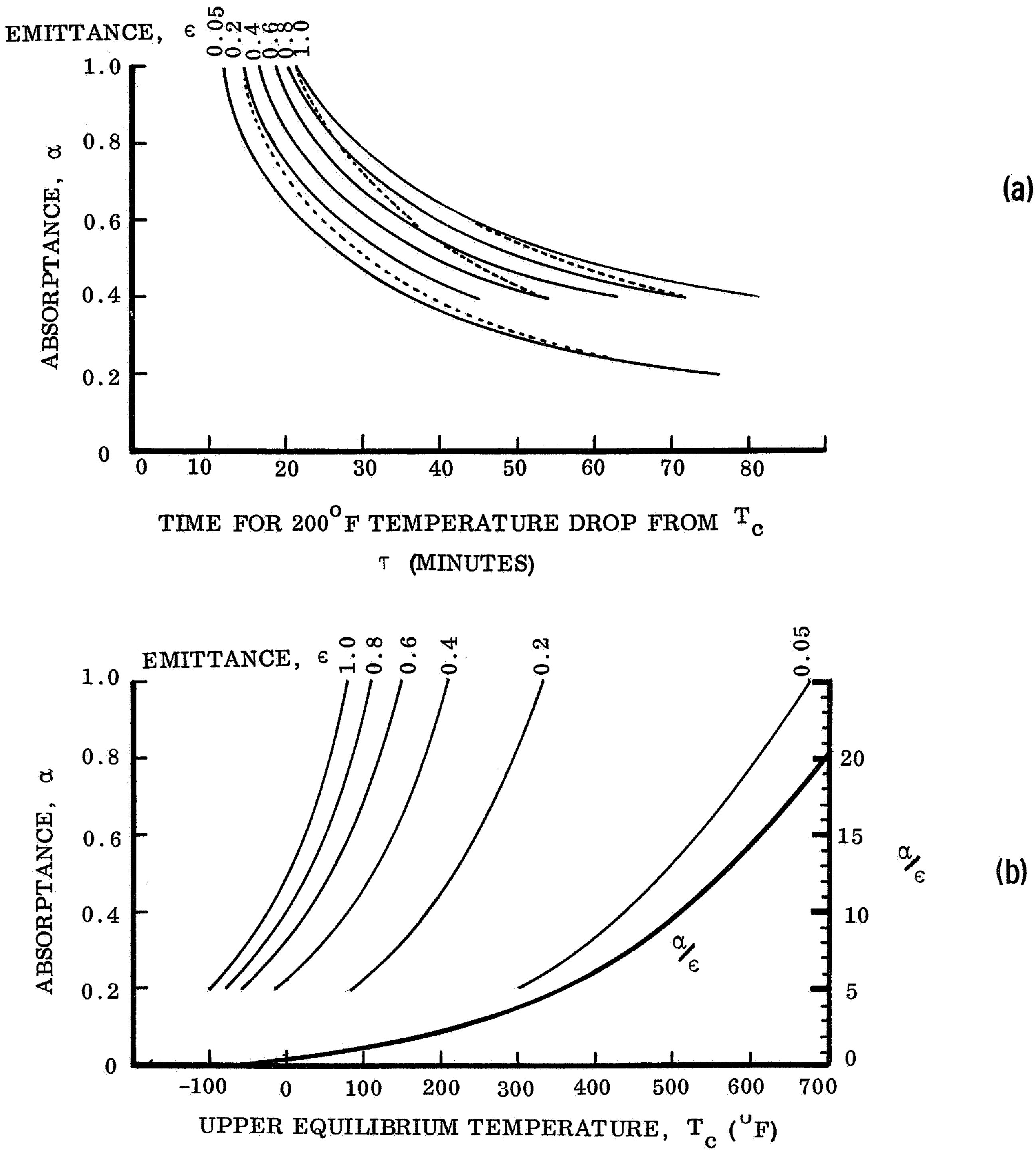
equating Q_i and Q_o and solving for T_c at equilibrium,

$$T_e = \left(\frac{\alpha}{\epsilon}\,\frac{S}{\sigma}\,\frac{A_p}{A_t}\right)^{1/4}$$

Figure 16b shows T_e as a function of α and ϵ or $\frac{\alpha}{\epsilon}$ ratio.

Since the solar flux is assumed constant, a surface with a relatively high absorptance is desirable to allow maximum heat input to the coil.

FIGURE 16
RADIATION COOLING TIME



ILLUMINATED COIL EQUILIBRIUM TEMPERATURE

3. Radiative Cooling

Cooling response depends on ϵ and initial temperature.

$$Q_o = \epsilon A_t \sigma (T_c^{\,4} - T_s^{\,4})$$

$$Q_o = M\, c\, \frac{dT}{d\tau}$$

equating Q_o terms and solving for τ between T_i and T_f at $T_s = 0$,

$$\tau = \frac{M c}{3\, \epsilon\, \sigma\, A_t} \left(\frac{1}{T_f^{\,3}} - \frac{1}{T_i^{\,3}} \right)$$

This relation is plotted in Figure 16a for a given coil. The curves indicated that a very high ϵ value does not necessarily indicate minimum cooling time. In fact, a low ϵ value coupled with a high α value may produce a coil with better thermal response. This is due to the fact that the resultant high $\frac{\alpha}{\epsilon}$ ratio produces a high initial equilibrium temperature. Radiative cooling to a zero sink is proportional to the fourth power of coil temperature, so a high initial temperature is desirable. The figure indicates that for most given cooling times, many α and ϵ combinations are possible.

4. Thermal Coatings

The curves in Figure 16b are plotted for ideal conditions, discounting conduction reflections, view factors, and non-zero sinks. They are helpful, however, in determining the type of thermal coatings necessary for coil elements. For the outside of the coil, a coating with properties indicated by the far left of Figure 16a is necessary. The inside of the coil radiates primarily to itself and therefore should have a coating with a high infrared absorptance. It should be noted that the coatings should be thin and conductive enough to prevent insulation of the coil. Since the coil is a flexing element, the coating should also be durable. Coatings conforming to above restrictions are presently being applied to sample bimetal elements for compatibility tests. Selected coatings will then be used on models tested in simulated orbit (thermal vacuum) conditions.

E. THERMAL HELIOTROPE CONCEPTS

The following paragraphs explain heliotrope concepts applicable to sun-tracking devices. The concepts are divided into four major categories: (1) continuous track and reset, (2) incremental advance and reset, (3) seasonal adjust, and (4) auxiliary devices. The first category consists of directly coupled devices; that is, the solar array is coupled through the bimetal coil to the vehicle. This necessitates an array reset and coil reset every orbit revolution of pitch axis tracking. The second category utilizes an incremental tracking principle. The array is not directly attached to the bimetal coil but rather through a ratchet interface allowing coil reset without resetting the entire array. These devices are also most applicable to pitch axis tracking. The third category uses both of the previous principles to provide a roll axis tracking range within plus or minus 60 deg of arc. The auxiliary devices category includes shade devices and torque multipliers.

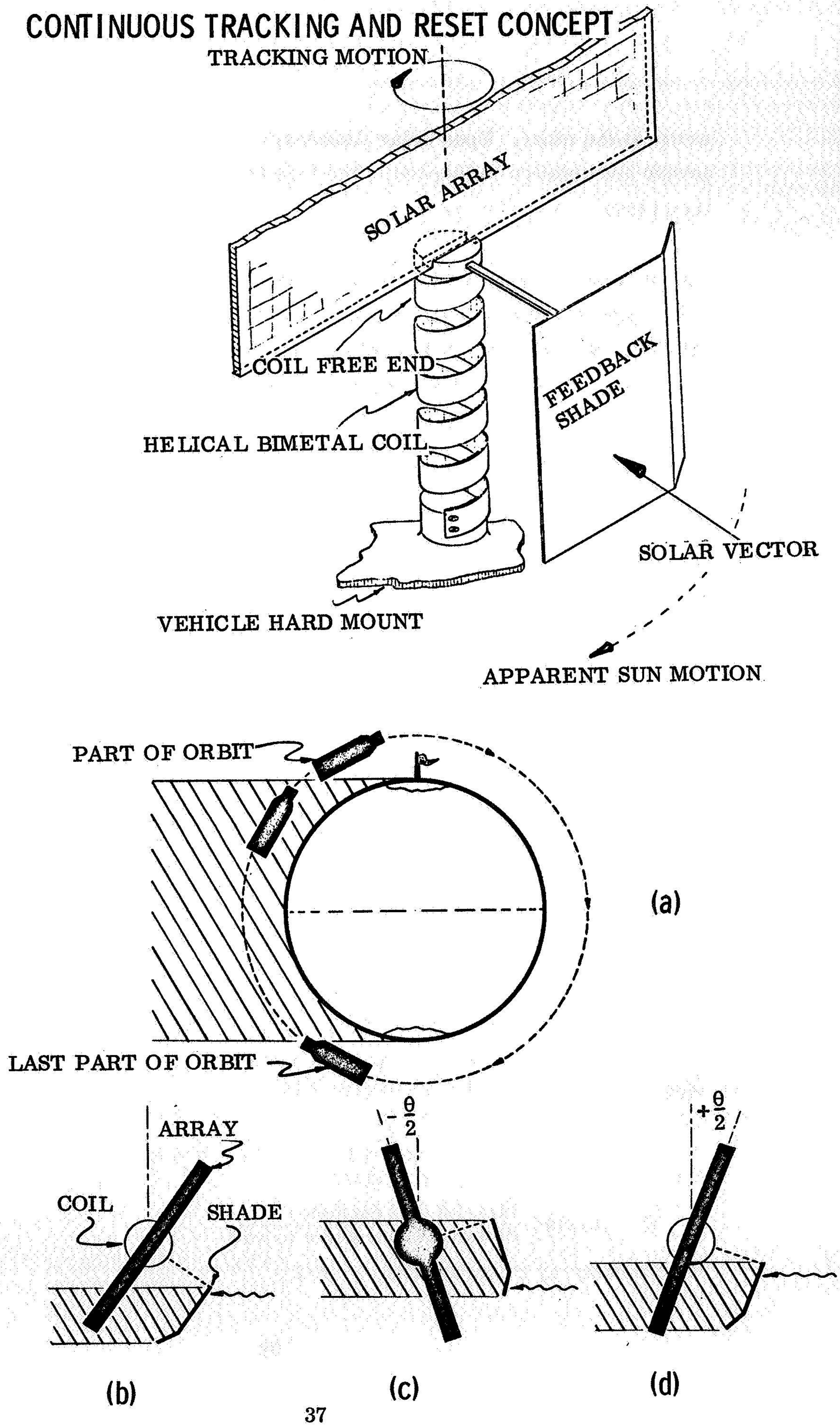
Conceptual designs illustrating the principles of operation of selected devices have been prepared. As of the reporting date, two models suitable for environmental testing have been designed. Construction of these test models is 70 percent complete, and testing is scheduled for early in the next reporting quarter.

1. Continuous Track and Reset Concept

Figure 17 illustrates schematically a reset-type tracking device. In this type of tracker a reset takes place once per orbit, thus eliminating the necessity of sliprings; a flexible wire harness will suffice for power transfer. This device is especially applicable to low earth orbits in which the vehicle is shaded for a period once per orbit. The device consists basically of a bimetal element and a feedback shade system. The bimetal element is fixed to the vehicle at one end and attached to the solar

FIGURE 17

CONTINUOUS TRACKING AND RESET CONCEPT



array at the other. Upon solar illumination, the coil temperature increases, and a torque and rotation is induced. The free end of the coil, and hence the solar array, then turns.

The bimetal coil is sized to produce more than the required angle of turn for available temperature rise. It is evident then that rate control is necessary. This is provided by throttling the amount of solar flux reaching the coil. A small shade, attached to the solar array, provides a feedback function and is called the feedback shade. An example of the feedback principle (Figure 17) will be given.

In Figure 17a the vehicle is about to enter the illuminated portion of the orbit after being eclipsed by the earth. The array is resting against a mechanical stop. As the array first enters the illuminated portion of orbit, the coil is fully exposed to solar heating (Figure 17b). A temperature rise in the coil causes the array to rotate counterclockwise. The array will continue to turn until the feedback shade covers most of the coil, as in Figure 17c . At this point the array is misoriented by $\theta/2$*. The shade then functions throughout the illuminated portion of orbit, limiting rotation to that needed to orient the array. The "over turning" tendency built into the coil sizing for the available temperature rise is controlled by the shading function of the feedback shade. At the end of the illuminated portion of the orbit, the coil has rotated 200 or more degrees of arc and is approaching its maximum temperature. The feedback shade is positioned as shown in Figure 17d, and the array is misoriented by $+\theta/2$.

At this point the vehicle enters the earth's shadow, and reset begins. The coil cools by radiation to the environment, and the entire array resets to a mechanical stop. Further coil cooling builds up a small torque restrained by the stop. The array is then ready to repeat the tracking cycle upon entering the illuminated portion of the orbit.

---

* θ is the angle of array rotation between fully shaded and fully illuminated coil modes and is a function of shade configuration:

$$\theta = \arctan \frac{\text{bimetal coil diameter}}{\text{distance from shade to coil}}$$

Maximum array misorientation is $\theta/2$.

If the orbit is such that an earth shade period does not occur once per orbit, an auxiliary mechanical shading device may be used to provide a coil-shade-reset period. These auxiliary shades are discussed under "Auxiliary Devices" in this section.

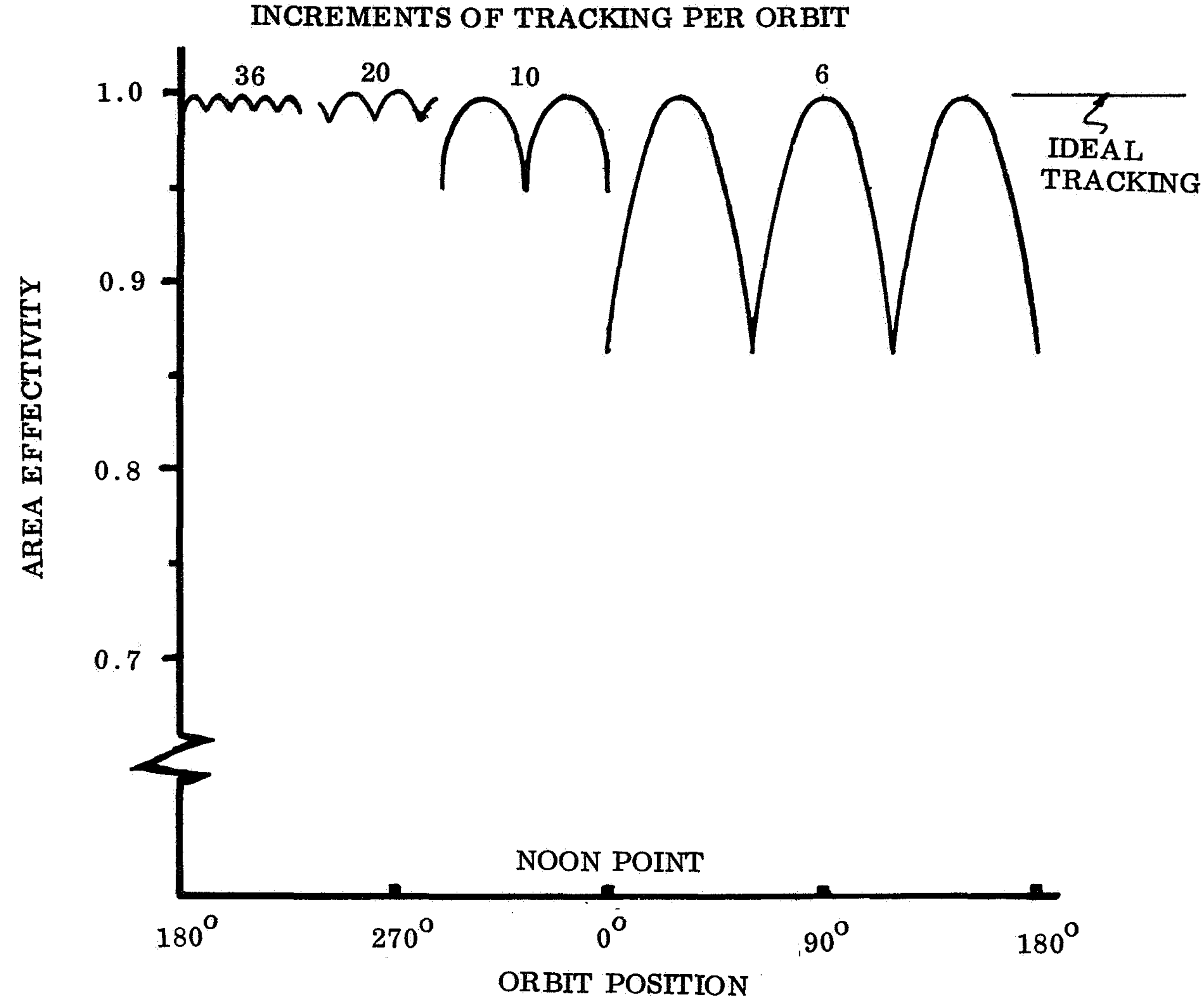
2. Incremental Advance and Reset Concept

Effective tracking may be accomplished incrementally instead of continuously. Figure 18 shows a plot of area effectivity vs. orbit position for various tracking increments. It is evident that the average area effectivity loss due to tracking in small increments compared to ideal tracking is very small. In an incremental device, the coil element advances and resets in increments and the array rotates unidirectionally. This type of non-array-reset device is well-suited for intermediate altitude and synchronous orbits in which a daily earth shade eclipse does not always occur. In orbits of this nature it is desirable to minimize battery cycling; therefore, a device that does not require an array reset once per orbit is required.

There are several types of incremental concepts possible. Four of these devices are described below.

a. Detent Devices. To explain the principle involved in incremental tracking, a schematic example of a detent device is shown in Figure 19. One end of the bimetal coil is fixed to the vehicle. The other end of the coil drives the array and a detent wheel through a ratchet interface. A combination feedback-reset shade attached to the array provides tracking control. In Figure 19a the array is oriented, and the coil completely shaded. As the vehicle travels through its orbit path, the array and shade become slightly misoriented (the amount depends upon shade configuration). As the cell becomes partially exposed (Figure 19b), the increase in coil temperature causes a torque increase. The array is prevented from turning by a spring-loaded detent. When the coil is nearly fully illuminated, enough torque is built up in the coil to rotate the array and detent wheel to the next detent. This may occur at 6 deg of angular misorientation, and the detents are spaced so that the next detent stop is 12 deg (in this particular example). Thus, the array rotates 12 deg of arc (Figure 19c). In this new position, the bimetal coil is completely shaded by the reset-feedback shade for 6 deg of orbit travel.

FIGURE 18
SOLAR PANEL AREA EFFECTIVITY vs. TRACKING INCREMENTS



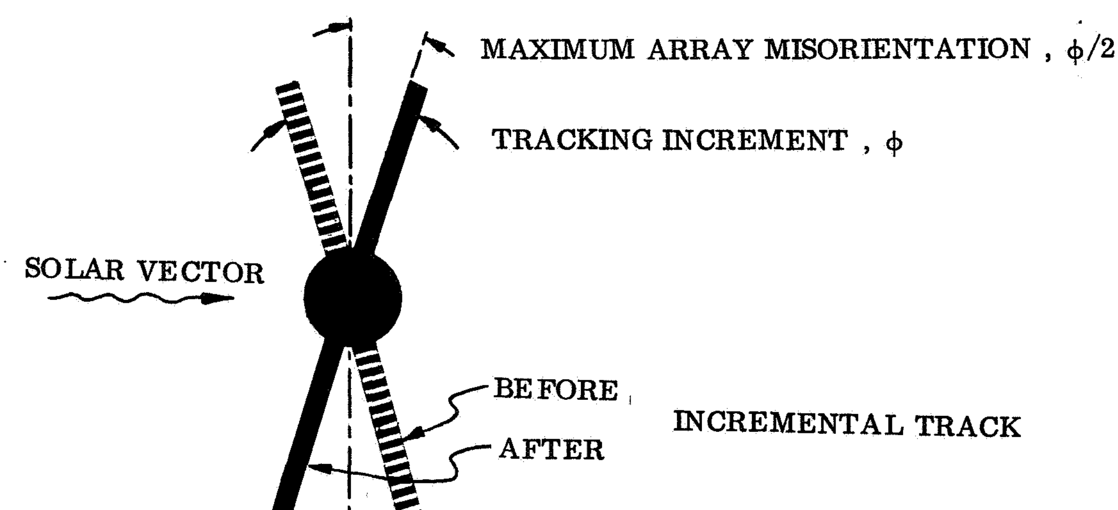
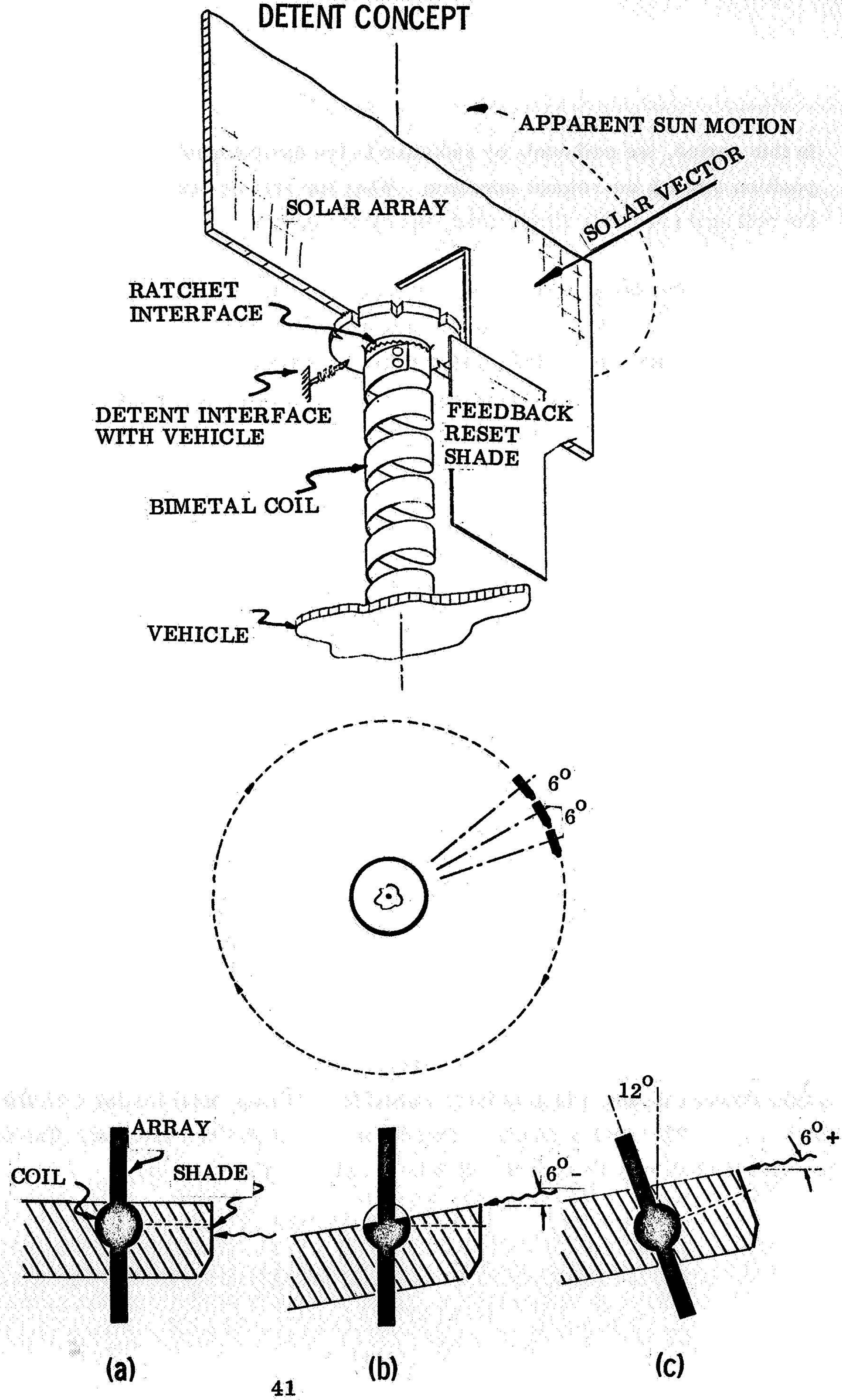


FIGURE 19
DETENT CONCEPT



In this period, the coil cools by radiation to the environment and resets to its cool position through the ratchet interface. When the vehicle reaches the point at which the coil again becomes illuminated, the cycle repeats.

b. Locking Ratchet Detent Device. The concept explained above may be applied to a physical device. A pictorial drawing of a locking ratchet detent device is shown in Figure 20. It was determined that to prevent detent overrunning (that is, rotation of the array past the following detent) due to inertial effects, a locking ratchet device should be incorporated. In Figure 20, the shaft is integral with the vehicle interface, and one end of the coil is affixed to the outboard shaft end. The other end of the coil drives a cam and detent wheel attached to a piece part called the concentric. The concentric assembly is free to rotate about the shaft. An arm and dog assembly controls the motion of the cog wheel (to which the array is attached). The locking tooth in the arm ensures that only one increment of array travel occurs per heating cycle of the coil. The device operates as follows: Array misorientation allows coil illumination and heating as explained in paragraph (a). Heating of the coil builds up cam torque which is restrained by the spring loaded detent assembly. (Note that the figure shows the device in a position just after an increment of tracking has taken place, and the coil has not yet cooled fully.) When nearly fully illuminated, the coil produces enough torque to overcome the detent force and rotate the cam. Rotation of the cam causes the follower to actuate the attached arm/dog assembly and advance the cogwheel one increment. The locking tooth on the arm prevents the cogwheel from traveling more than a single increment. In this new position, the coil is shaded by a shade attached to the array-cogwheel unit, and the coil cools. This cycle repeats for further tracking.

c. Brake Detent Device. Figure 21 shows a drawing of a device incorporating the brake detent concept, which is more suited for environmental testing than the above device (b) . This unit is enclosed except for the bimetal coil element. The outside enclosure shell may be considered to be attached to the solar array.

FIGURE 20

LOCKING RATCHET DETENT DEVICE

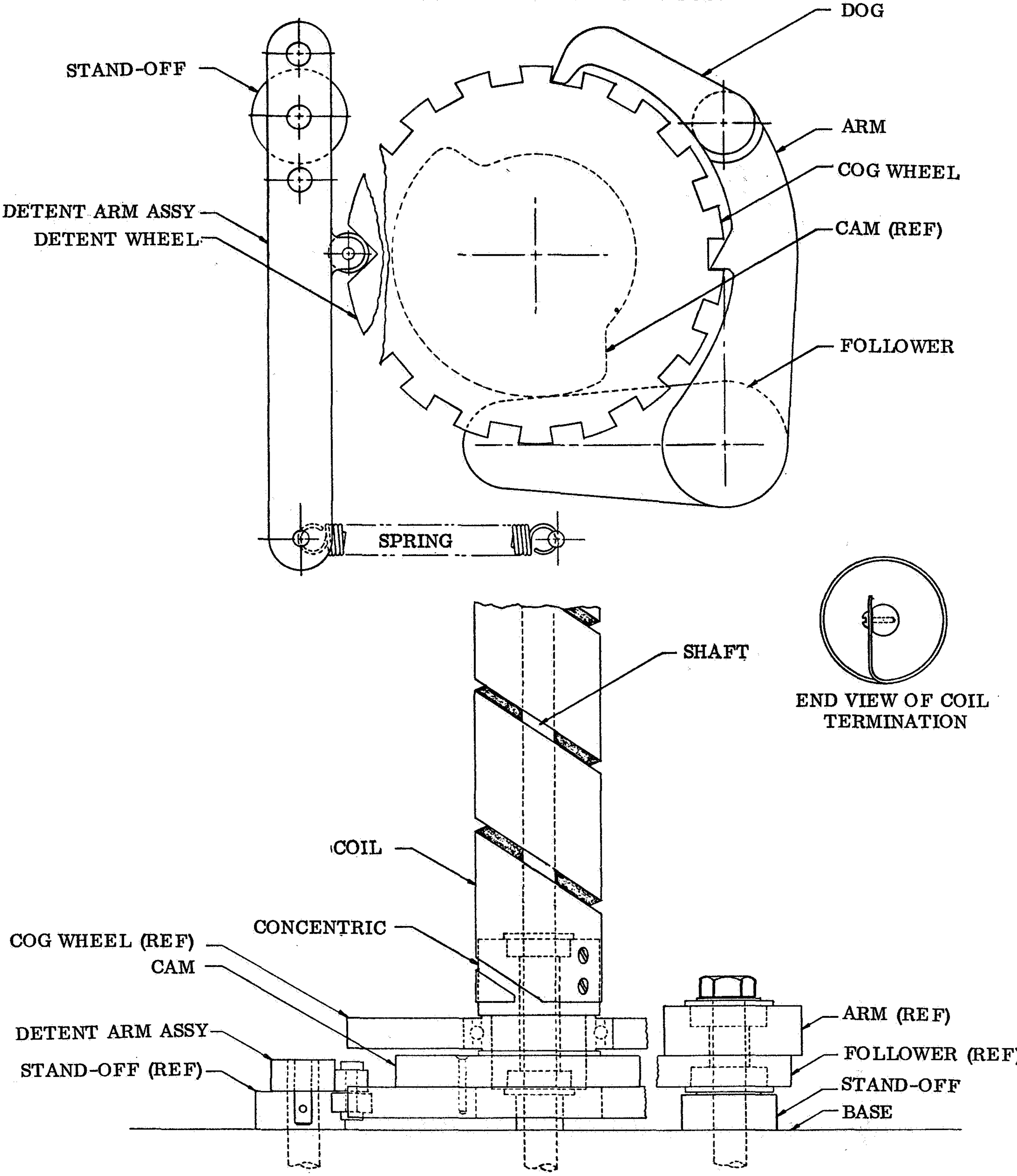
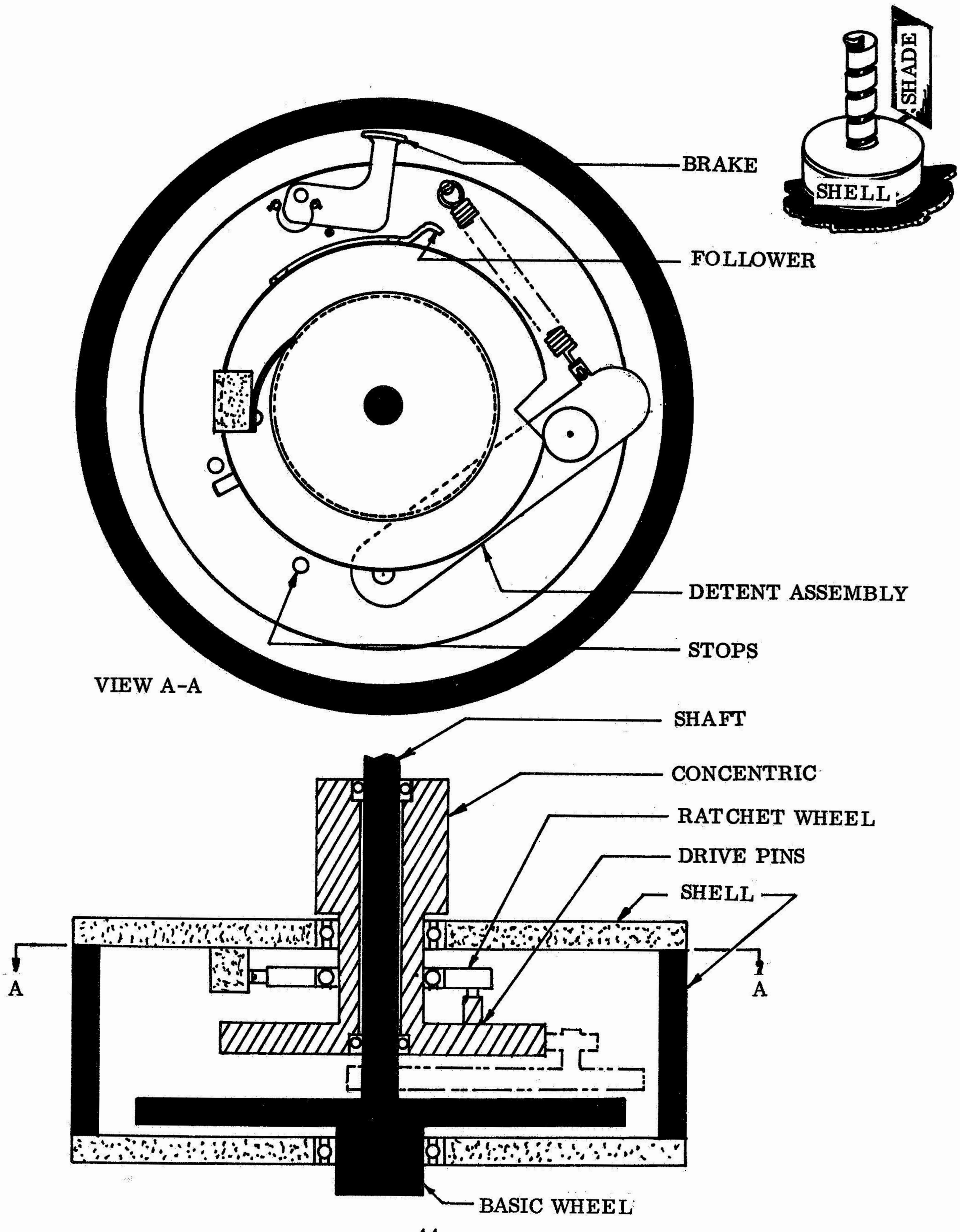


FIGURE 21
BRAKE DETENT DEVICE



An explanation of operation modes follows: The base wheel and shaft are fixed to the vehicle, and the bimetal coil is fixed to the outboard end of the shaft. The other end of the coil rotates the concentric, which is restrained by a spring-loaded detent. The concentric has drive pins that mate with pins on the ratchet wheel. This wheel in turn works through a ratchet interface with the outside shell. The pins do not engage until the detent arm has been lifted fully in order to avoid excessive array misorientation. As before, misorientation of the array allows solar illumination to pass a shade (not shown but attached to the array) and heat the bimetal coil. Torque is produced until enough is stored in the coil to overcome the detent spring force. The concentric then turns an increment governed by pre-set mechanical stops and engages the ratchet wheel. The ratchet wheel in turn rotates the outside shell (with array and shade). In the new position the coil is shaded, and reset takes place through the ratchet interface. A scheme for preventing overshooting due to system inertia incorporates the braking principle. After the concentric travels one increment, the attached spring follower activates a small brake to prevent over rotation of the shell and array. The array is then locked until the bimetal coil cools.

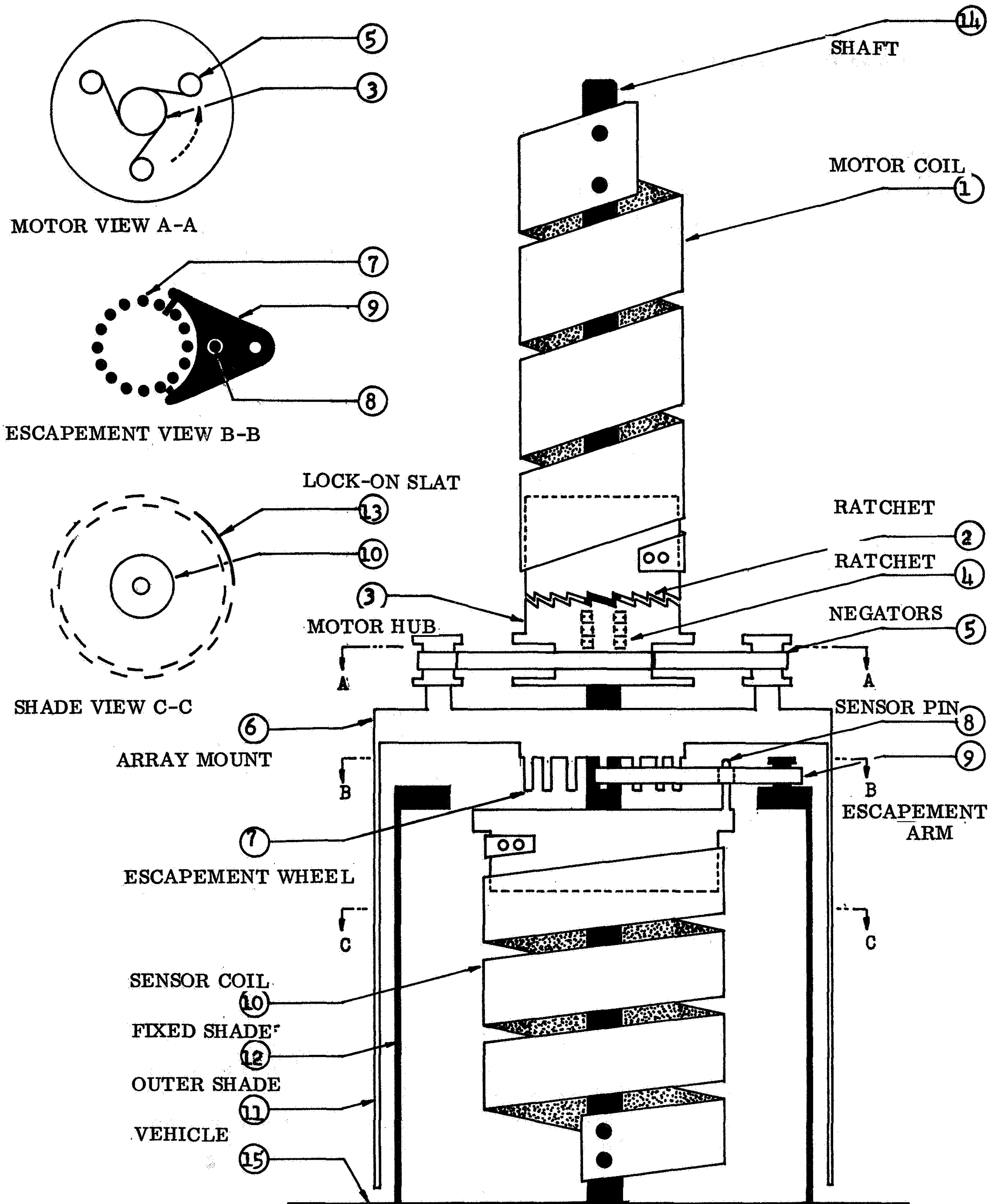
d. Stored Energy Device. The preceding concepts are somewhat limited in capability in that they must have a heating and cooling cycle to produce motive force for each increment of tracking. If one increment of tracking does not initially orient the array and shade the coil, reset cannot take place. This problem is minimal for a no-shade orbit vehicle since after the initial revolution the tracker would begin tracking as designed. However, for the sake of reliability and versatility, a device capable of orienting a solar array from any degree of misorientation is desirable.

The device shown schematically in Figure 22 is a tracker compatible with most orbit situations including gross misorientation. It incorporates a stored energy principle and is called a stored energy device.

Energy Storage Mode

- Once per orbit the motor coil (1) experiences a heating cycle due to solar illumination and a cooling cycle due to shading. The shading is provided by either earth eclipse or a vehicle-mounted shade.
- The heating and cooling of the motor coil produces an oscillating rotation of its free end. Note the shaft (14) is fixed to the vehicle.

FIGURE 22
STORED ENERGY DEVICE



- A ratchet (2) between the motor coil and the motor hub (3) allows a winding motion of the motor hub.
- Another ratchet (4) provides an interface with the shaft to allow only unidirectional rotation of the hub.
- The unidirectional rotation of the motor hub reverse winds the elements of negator springs (5) on to the hub.
- As shown in the motor view, the springs produce a constant torque on the array mount interface (6) in one direction.

Tracking Mode

- The solar array is attached to the array mount (6). To control rotation of the array mount, an escapement wheel (7) is used.
- The escapement arm (9) is actuated by the sensor pin (8). For each heating and cooling cycle of the sensor coil (10) the escapement slips two increments (see escapement view).
- Attached to the array mount is a slotted shade (11) concentric with another slotted shade (12) fixed to the vehicle (see shade view).
- The shades are mechanically synchronized with the escapement so that the sensor coil is alternately illuminated and shaded.
- When the slots in the shades align, the coil is illuminated. This will cause the sensor pin to actuate the escapement and allow the array to rotate one increment.
- This rotation closes the shades, and the coil begins to cool.
- When the coil cools, another escapement motion takes place and the coil again becomes illuminated with another increment of array mount and shade rotation.
- This cycle repeats until the lock-on slat (13), which is coplanar with the solar array, is normal to the sun. In this position, the sensor coil is shaded. The array remains in this position until misorientation again causes the sensor coil to become illuminated.

3. Seasonal Adjust Concept

The third main concept in tracking devices is the seasonal adjuster. This device provides tracking in the roll axis of the vehicle and must often be capable of bidirectional tracking in the range of ±60 deg. In many low altitude, earth-orbiting missions it is not feasible to use a continuously tracking array due to propulsion weight penalties associated with drag makeup. In these cases the arrays are deployed in the pitch-roll plane such that the array leading edges present a minimum frontal profile to the line of flight. Small incremental changes in the array position about the roll axis of the vehicle, alpha angle adjustments, can dramatically improve array output by repositioning the array. Figure 23 illustrates the results of a study to determine the necessity of these seasonal adjustments. This particular study was for a low orbit case of about 150 nm. The effectivity curves will shift upward with increasing altitude.

A conceptual sketch of an alpha adjuster is shown in Figure 24. Solar flux passing on either side of the adjustment shade activates one of the adjustment helices, and position correction takes place. The operational range shade allows adjustments to happen only as the vehicle passes through the ecliptic plane. This is the optimum position for seasonal adjustment.

4. Auxiliary Devices

Auxiliary devices consist of shading and reset devices and torque multipliers.

a. Shading and Reset Devices. Auxiliary shading and reset devices are schemes for providing the coil reset function when a natural earth eclipse does not occur. These units may be used as an addition to or as a substitution for earth eclipse. Several types of reset devices are mentioned below. To date all of these devices are in the concept stage with the exception of the slotted shade.

- Fixed Shade – A shade fixed to the vehicle proper will provide a daily shade period for the thermal heliotrope element. The dwell of this shade is a function of shade width and distance from the element. This type of shade is especially suited for cycling the energy storage mechanism on the unit described previously as the "stored energy device."
- Snap Acting Bimetals – Several types of snap action devices may be fabricated utilizing bimetal elements. Snap disks provide a snap action from a cold position to a hot position, as shown in Figure 25a. The snap takes place at a given pre-set temperature. Another example of a snap bimetal is the Wilco-Taylor thermometal blade (Ref. 5) shown in Figure 25b. The blade is formed from flat stock by buckling the end section. Upon heating the buckled section will restrain temperature deflection until enough force is developed for a snap to occur. The blade may be designed to provide an increased cold-contact-point pressure up to the point of snap by sizing the center leg so that its initial deflection is greater than that of the outer legs. By doing this, holding force of the unit is not sacrificed before snap action occurs.

FIGURE 23
IMPROVEMENT IN ARRAY EFFECTIVITY AS A FUNCTION OF SEASONAL ADJUSTMENTS

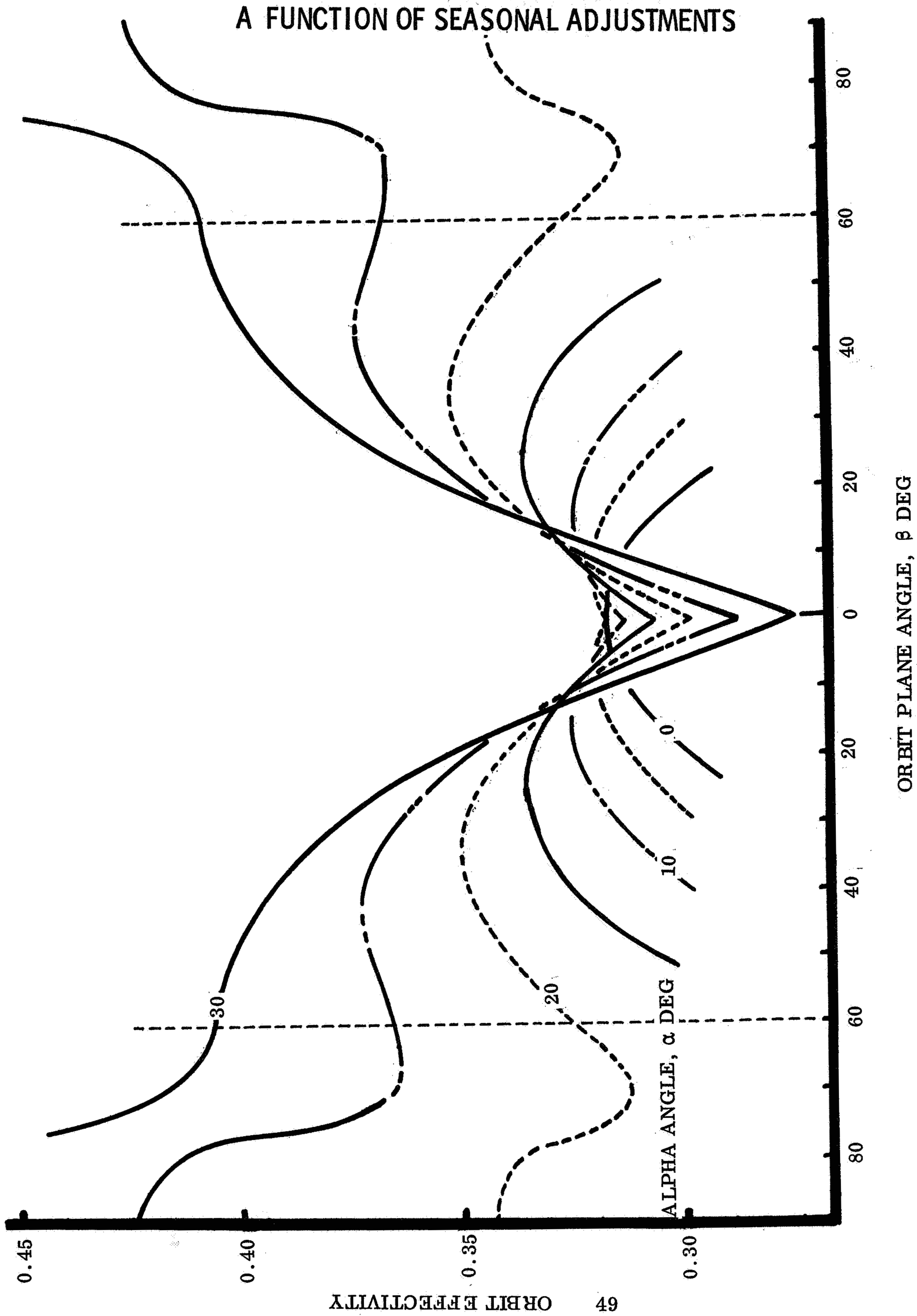


FIGURE 24
ALPHA ANGLE ADJUSTER CONCEPT

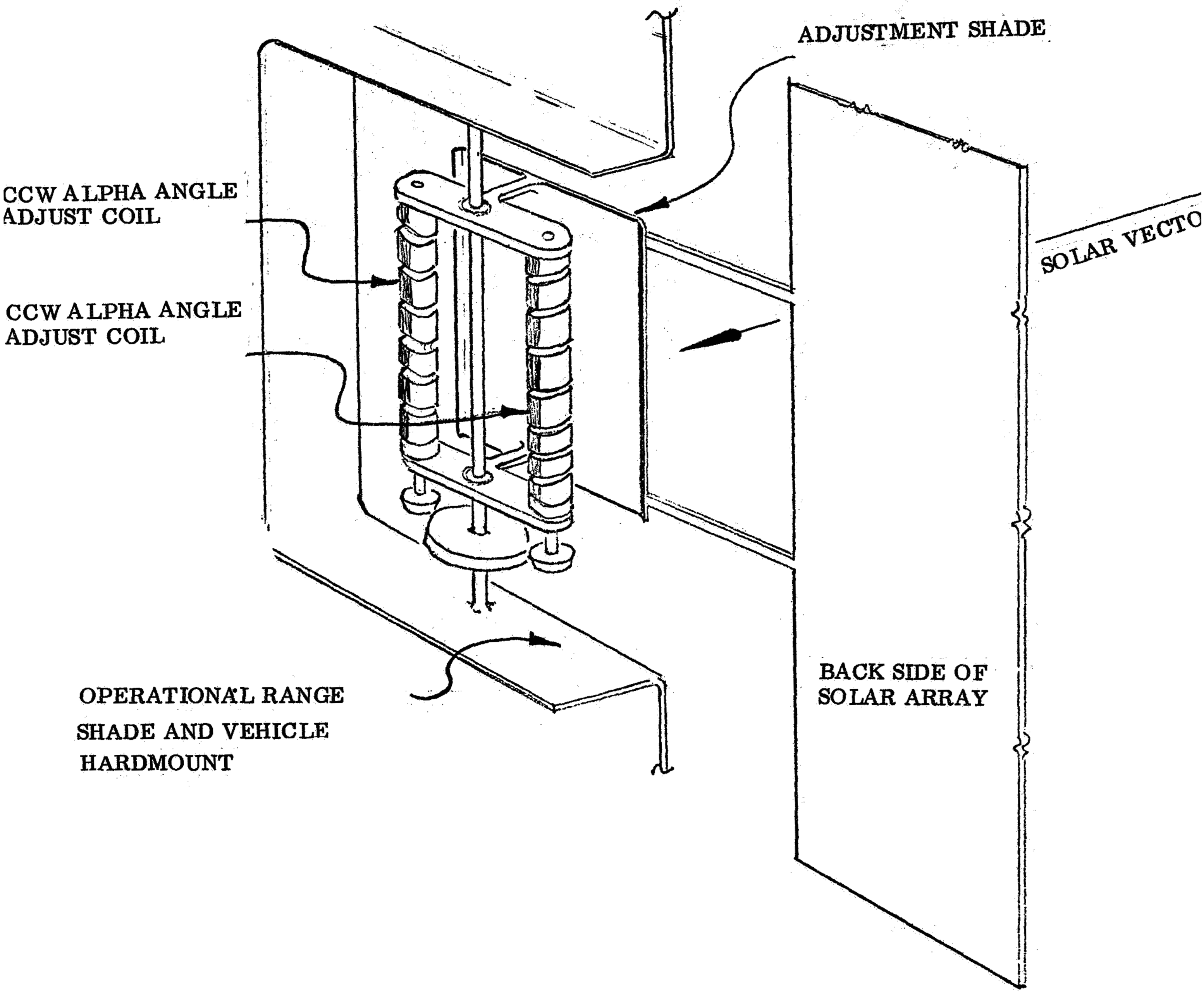
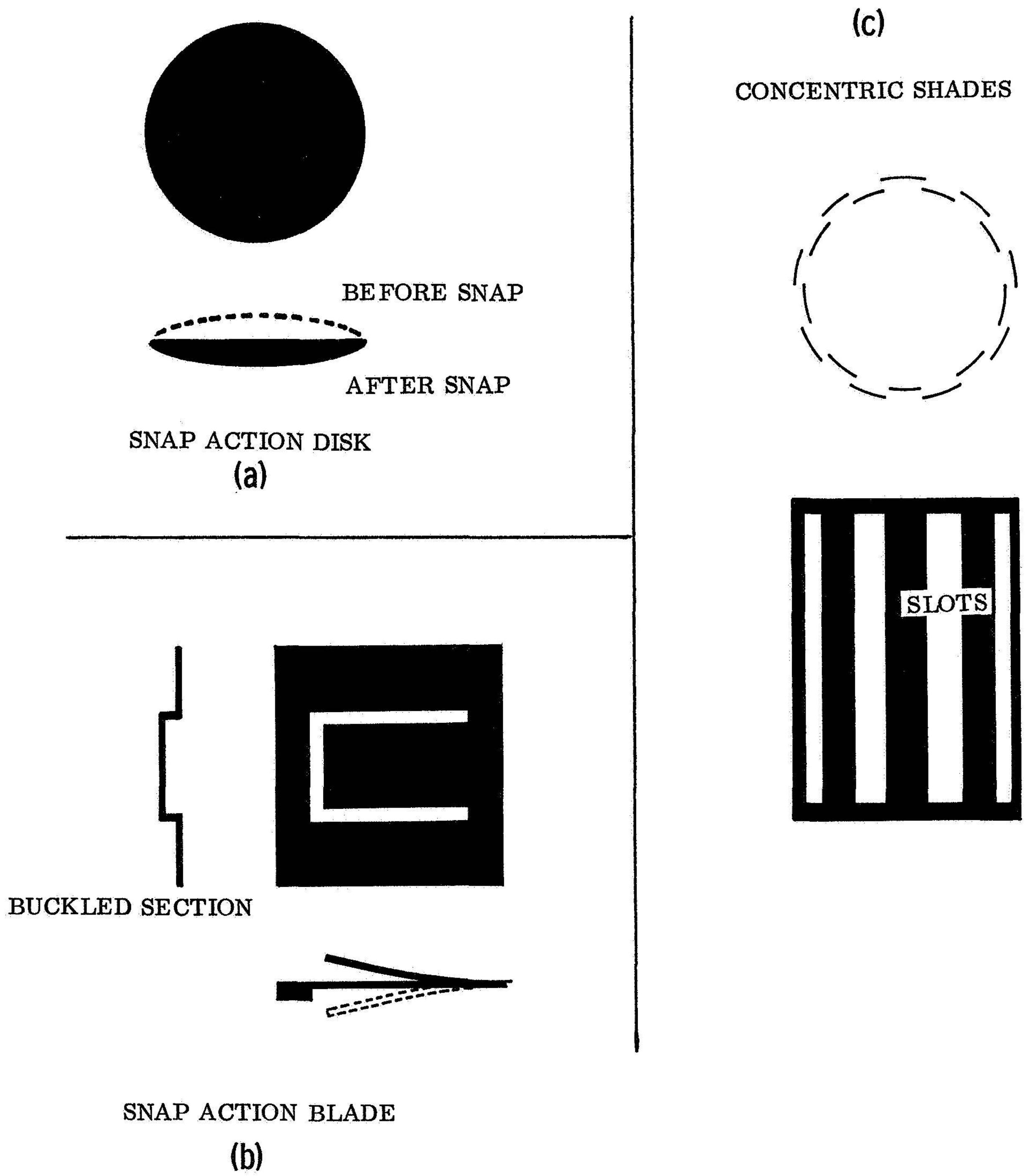


FIGURE 25
AUXILIARY DEVICES

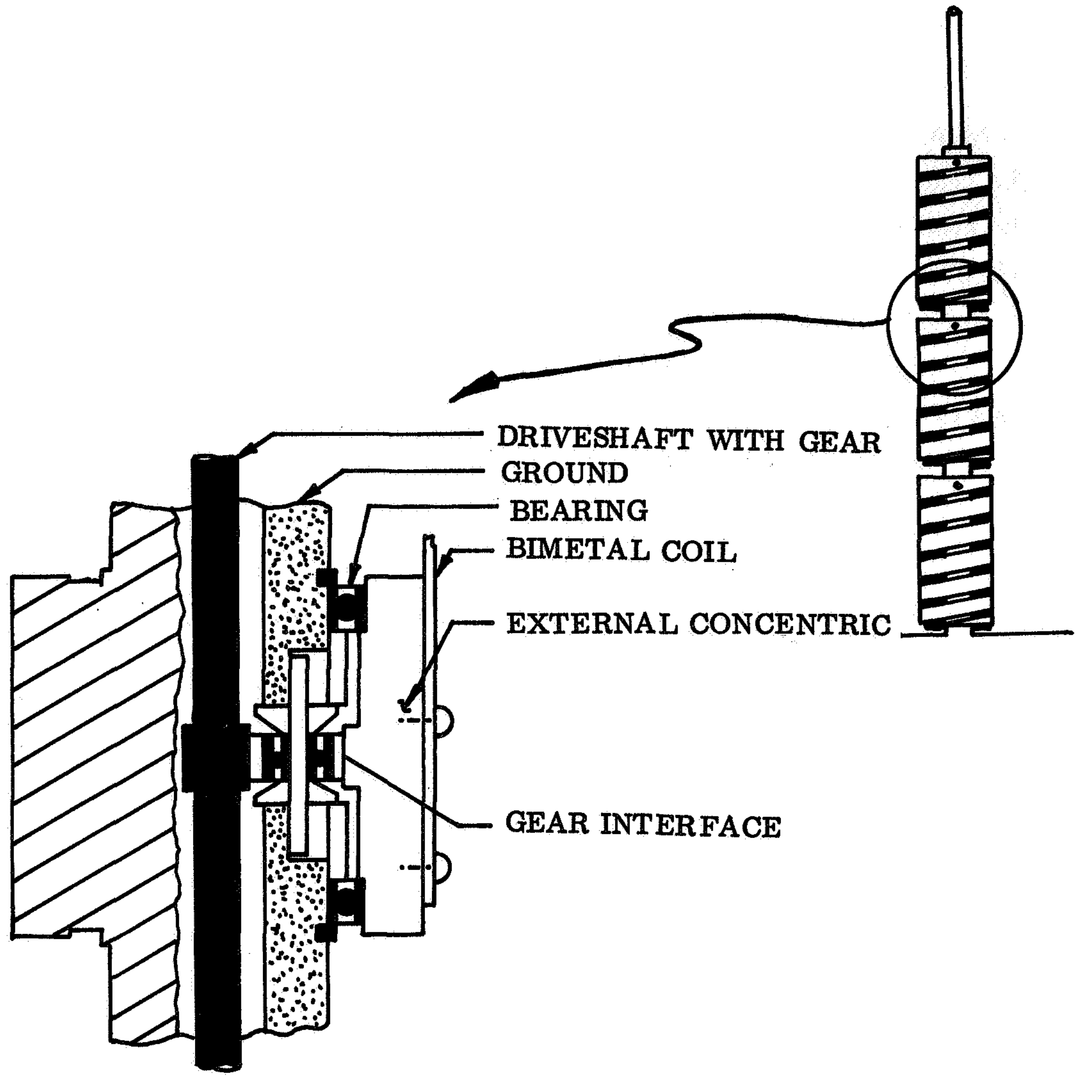


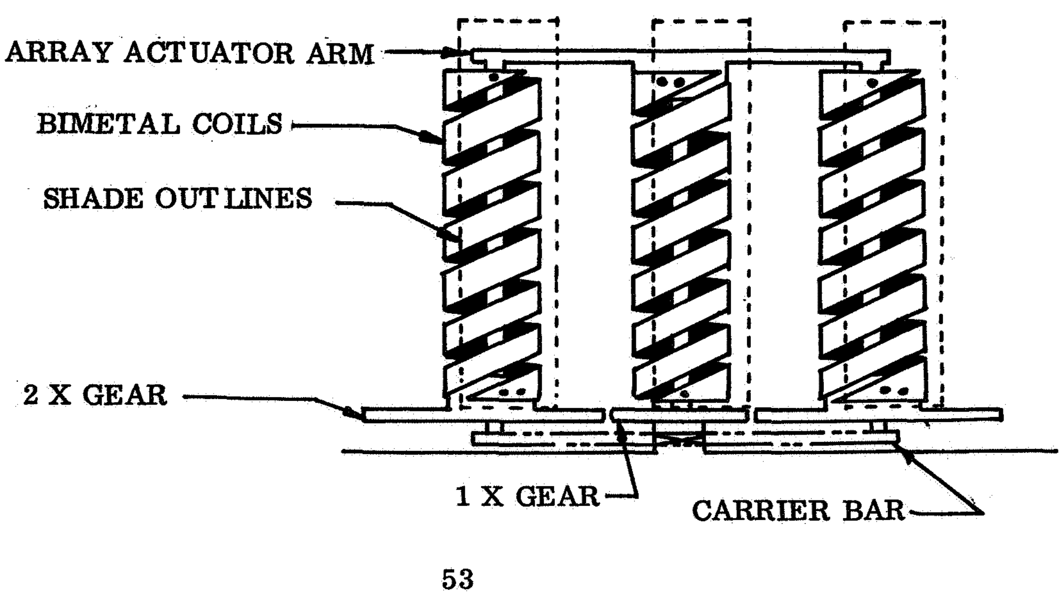
- o Coiled Bimetals – An auxiliary helical bimetal coil may be used to turn a shade into position by rotary motion. Energy reaching this auxiliary coil is governed by shades attached to the solar array or the vehicle. Linear motion may be achieved by winding a coil into a double helix. Motion is then in the direction of the major helix.
- o Solenoid – An electrical solenoid may be used to actuate a coil reset shade very easily. However, even though a solenoid may be a fairly reliable device, it is the point of this study to provide completely passive (non-electrical) tracking functions.
- o Slotted Shade – One of the most promising shade applications is a device that uses two concentric cylinders. Slots are opened in the cylinders at given increments as shown in Figure 25c. Rotating one cylinder one increment with respect to the other will alternately open and close the slots. This allows heating or cooling of a bimetal coil housed within the inner cylinder. This particular device is being used on the "stored energy tracker" model presently under construction.
- o Mechanical Trip – A reset shade may be actuated as a function of solar array position with respect to the vehicle. Here a trip on the array actuates a shade when the array achieves a given position. Multiple trips may provide a given shade time dwell.

b. Torque Multipliers. Torque multiplication may be necessary to overcome friction and inertia associated with large solar arrays. For a given width and thickness coil, torque may be increased by either gearing down or parallel mounting of bimetal elements. Gearing down is quite straightforward. It consists of taking a coil of relatively long length (thus capable of many revolutions for available temperature change) and gearing it down by the desired torque multiplication ratio. On the overview it might seem that in order to gear down a coil for a multiplication factor of 3:1, the coil would be three times as long as normal and have one-third the mechanical torque. This is true; however, from the bimetal equations (see the Bimetal Theory section) it may seem that the thermal torque is independent of coil length. That is, for a given temperature rise, the restrained torque produced in a helical coil of specified width and thickness does not change with length. Hence, the gearing down approach to torque multiplication is valid. Parallel mounting of bimetal coils is another approach for increasing available tracking torque. Figure 26 shows two concepts for parallel coil drives. The first method appears to be a series configuration, in that the coils are mounted in one axis. However, each coil is grounded at one end, and the free end drives a shaft internal to the ground tube. Figure 26 shows a true parallel mounting scheme. To avoid coil shading by neighboring coils, the entire assembly rotates with

FIGURE 26

TORQUE MULTIPLYING CONCEPTS





the solar array. The center coil is attached to a fixed shaft and gear at the base. The free end of this coil turns an actuator arm to which the outboard coils are attached. The free ends of those coils transfer torque through gears to the fixed center unit. Therefore, all the torques generated in the coils are transferred to the array through the actuator arm. The outboard gears are twice the size of the fixed gear, since they must rotate around the fixed unit. If they were the same size, it would take two revolutions of the outboard coils to turn the assembly one revolution about the center axis. To avoid different sized coils, the 2:1 gearing is used.

Torque multiplying devices may be necessary for directly coupled devices such as those suggested in the continuous track and reset concept. Incremental devices, however, have more torque capability and will probably not need auxiliary torque multipliers.

SECTION III
NEW TECHNOLOGY

New technology reported during this period includes the stored energy tracker. This device is described in Section II. It incorporates the use of two bimetal helices, one as a motor coil that winds a negator spring assembly and one as a sensor coil that activates an escapement. The escapement allows spring assembly/array rotation in discrete increments as a function of alternate illumination and shadowing via concentric cylindrical slotted shades.

The other concepts evolved are adaptations of devices developed under ID funding at LMSC prior to this program or ideas which, within the period reported, have not been sufficiently reduced to design or apparatus category to enable disclosure.

SECTION IV

PROGRAM FOR NEXT REPORTING PERIOD

The work performed during April, May, and June 1969 will constitute the second quarter of effort for this program. Task II, developing thermal heliotrope concepts for the common orbits, will be completed and Task III, performing thermal and mechanical analysis of selected design concepts, will be initiated. Task II effort will be a continuation of concept development similar to those contained in this report. The Task III activity will detail the operational characteristics of selected concepts, determining operational response as a function of component design, material, and thermal coatings in orbital environments of interest. An exploratory Task IV test will be conducted in May to evaluate the response characteristic of engineering models. This is a minor departure from the initially projected schedule, but it will be within labor/cost allocations and will enhance the value of the major test to be conducted in the third and final quarter of this program.

SECTION V
CONCLUSIONS AND RECOMMENDATIONS

1. Relatively low tracking rates produce very low torque requirements for thermal trackers.

2. A capability for recovery from a worst-case tracking-axis misorientation is a design objective for the trackers.

3. Counterclockwise, unidirectional tracking will satisfy most earth orbital tracking requirements.

4. Detailed tracker designs are dependent upon specific vehicle application factors including orbit, array size, vehicle/array space allocation and placement, and vehicle guidance and control restraints.

5. It is desirable to optimize the bimetal coil thermal response through appropriate thermal coatings. Maximum cooling response is obtained by utilizing the high equilibrium temperature derived from coatings with high values of absorptance and low emittance.

6. The thermal torque capacity of a bimetal coil varies directly with temperature change and element width and with the square of element thickness. Thermal response varies directly with element thickness, a thinner coil being more responsive.

7. A locking or breaking device is necessary on detent/snap concepts to prevent overrun due to system inertia.

8. Energy may be stored in a spring motor and triggered by a bimetal sensor. This allows a high torque motor coil and a high response sensor.

SECTION VI
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